Keck
INSTITUTE FOR SPACE STUDIES

Small Satellites: A Revolution in Space Science

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Workshops: July 2012 and October 2012
Image: Earth-Sun L5 Space Weather Sentinels Constellation Concept

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1 Executive Summary

1.1 Introduction

This report describes the results of a study program sponsored by the Keck Institute for Space Studies (KISS) at the California Institute of Technology to explore how small satellite systems can uniquely enable new discoveries in space science. The disciplines studied span astrophysics, heliophysics, and planetary science (including NEOs, and other small bodies) based on remote and in-situ observations. The two workshops and study period that comprised this program brought together space scientists, engineers, technologists, mission designers, and program managers over 9 months. This invitation-only study program included plenary and subject matter working groups, as well as short courses and lectures for the public. Our goal was to conceive novel scientific observations, while identifying technical roadblocks, with the vision of advancing a new era of unique explorations in space science achievable using small satellite platforms from 200 kg down to the sub-kg level.

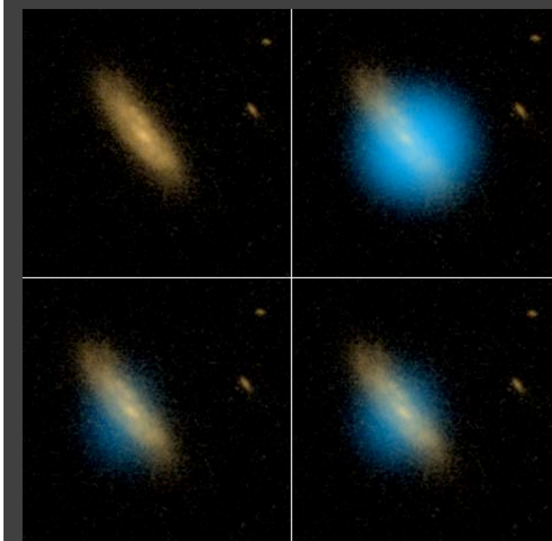
The study program participants focused on the role of small satellites to advance space science at all levels from observational techniques through mission concept design. Although the primary goal was to conceive mission concepts that may require significant technology advances, a number of concepts realizable in the near-term were also identified. In this way, one unexpected outcome of the study program established the groundwork for the next revolution in space science, driven by small satellites platforms, with a near-term and far-term focus.

There were a total of 35 KISS study participants across both workshops (July 16-20, 2012 and October 29-31, 2012) from 15 institutions including JPL, Caltech, JA / PocketSpacecraft.com, MIT, UCLA, U. Texas at Austin, U. Michigan, USC, The Planetary Society, Space Telescope Science Institute, Cornell, Cal Poly SLO, Johns Hopkins University, NRL, and Tyvak LLC. The first workshop focused on identifying new mission concepts while the second workshop explored the technology and engineering challenges identified via a facilitated mission concept concurrent design exercise. The Keck Institute limits the number of participants per workshop to at most 30 to encourage close interaction where roughly 20% involved in this study were students.

This report is organized to communicate the outcome of the study program. It is also meant to serve as a public document to inform the larger community of the role small satellites can have to initiate a new program of exploration and discovery in space science. As such, it includes recommendations that could inform programmatic decision making within space exploration agencies, both in the USA and internationally, on the promise of low-cost, focused, and high impact science should a strategic plan for small satellite space science be pursued. As such, the study program organizers and all participants are available to respond to any aspect of this report.

1.2 Defining New Mission Concepts

The first five-day workshop started with a short course held at the Lees-Kubota Lecture Hall at Caltech. The short course was open to the community leading with a keynote talk by Professor Shri Kulkarni on the "Less Is More Satellite" (LIMSat). LIMSAT is a proposed low mass and low cost small satellite constellation mission of eight telescopes designed to carry out a wide-field UV transient survey. It is aimed at studying shock breakouts of supernovae producing important science at low risk. With an instantaneous field of view of 1,200 square degrees (covered by eight telescopes) LIMSat expects to detect a shock breakout every month. When compared to a mission like GALEX, LIMSat has a sensitivity goal approximately ten times less with a field of view goal that is approximately 1,000 times larger. If these requirements were met, LIMSat would have a detection rate 30 times higher than GALEX based on a small satellite design.



Supernovae shock breakout (NASA)

AAReST
Autonomous reconfigurable telescope concept
(California Institute of Technology, Surrey SC)

Additional talks from the short course covered small satellite functional design, new CubeSat science observations based on NSFs CubeSat-based Science Missions for Geospace and Atmospheric Research program, engineering capabilities of CubeSats and ESPA-class sized small satellites, and mission concepts to address new scientific questions in planetary science concluding with an expert panel on new exploration concepts in astrophysics.

The formal part of the meeting involved a program structured to identify new concepts uniquely enabled by the small satellite platform. Study sessions started with plenary lead-in talks in astrophysics, heliophysics, and planetary science followed by breakout group discussions on possible scientific observations enabled by small satellites. The groups reported on their progress in the subsequent sessions followed by plenary meetings to begin identification of potential common engineering challenges associated with the new mission concepts.

The set of potential concepts, three per focus area, are listed in the following table. The astrophysics concepts are RELIC, SoftX, and UVIP-UV Reionizaton Probe. These mission concepts were selected to span most of the spectrum where important scientific discoveries could be made. The heliophysics concepts are IMCC, Solar Polar Constellation, and Fractionated L5 Space Weather Sentinel Constellation. They emphasized large-scale first-of-a-kind multipoint physics measurements that take advantage of distributed and fractionated small satellite observation capabilities. The planetary concepts are ExCSITE, C/entinel, and Lunar Cube Vibrations. These were largely multi-scale spacecraft systems using a few host spacecraft with hundreds to thousands of observers. These nine concepts represent the final set proposed within focus groups during the first workshop, but there were many other ideas generated during discussions, like the CHAMPAGNE planetary ring explorer concept, that is briefly introduced as well.

Mission Concept	Science Observation	Observing Strategy	Payload Technologies
RELIC	Understanding energy transport from black holes to the intergalactic medium.	Aperture synthesis imaging with a 1 km diameter spherical array of 30+ 3U CubeSats imaging doubled-lobed active galaxies at freq. below 30 MHz. Deployment at Earth-Sun L2 or low gravity gradient environment beyond the Moon.	5-meter dipole antennas in all 6-axes. Formation flying, constellation management, data downlink, antenna deployment, in situ data analysis and correlation management.
Soft-X	Measurement of the low-energy diffuse background from the interstellar medium	X-ray spectroscopy mission in sun-sync orbit observing away from Earth at 1-2 deg spatial resolution over the entire sky.	X-ray spectrometer detector from 100-1000 eV with a single collimator. Collimated CCD or CMOS detector and on-board

			processor for X-ray photon counting
UVIP-UV Reionization Probe	Understanding the source and mechanisms for reionization in the universe.	UV coarse spectral wide area survey imaging in LEO with a graduated "A-train style" constellation of ESPA-class small satellites.	Arc-second resolution, 912-2400 AA band, ~25cm aperture optics with CCD UV detectors. Pointing stability, UV coatings, high efficiency UV detectors.
Ionosphere Magnetosphere Coupling Constellation (IMCC)	Global electro-dynamics of Earth's magnetosphere-ionosphere coupling.	In situ measurements by 60 nanosatellites on 6 high inclination orbital planes supported by existing ground assets.	DC magnetometer, AC magnetometer, Langmuir probe, low-energy plasma instrument, energetic particle and electric field instrument.
Solar Polar Constellation	First dedicated solar polar constellation mission for understanding variability, dynamo, and Solar System effects.	Constellation of 6-12 identical CubeSats in high inclination solar orbit.	Heliophysics imager, DC magnetometer, low-energy plasma instrument, energetic particle detector, magnetograph.
L5 Space Weather Sentinels (L5SWS)	Space weather monitoring from the Sun-Earth L5 point: observe Earth-directed CMEs, monitor solar wind stream structure, see solar active regions before visible from Earth.	Combine remote sensing and in-situ instruments at Earth-Sun L5 using solar sails. Fractionate the mission into multiple 6U CubeSats for in-situ fields and particles, heliophysics imager, magnetograph and telecom building up observation capability incrementally.	Propulsion capability and station keeping at L5, relay communication, instrument packaging and miniaturization, arc-minute pointing stability.
ExCSITE	Characterization of Europa's surface via high-resolution imaging, gravity field mapping, and chemical characterization of dust ejecta.	Multiple deployed fly-by systems as CubeSats and/or SmallSats, including impactors for surface experiments, with support from host spacecraft.	Dust detectors, deployable impactor shields, fast high-resolution imaging cameras, particle and fields instrumentation, and proximity operations.

C/entinel	In-situ and proximity operations around small bodies including surface, deep interior, and origins of these systems.	Multiple fly-by and in-situ landers, deployed as CubeSats with support from larger host spacecraft.	Thermal and mineralogical sensors, spectrometers, entry-descent-landing,
Lunar Cube Vibrations	Mapping and characterization of the lunar interior and the search for volatiles and organics.	Multiple fly-by and in-situ landers, deployed as CubeSats and/or ChipSats with support from larger host spacecraft.	Seismometers, thermal sensors, magnetic field and dust sensors.

1.3 Assessing Engineering Feasibility

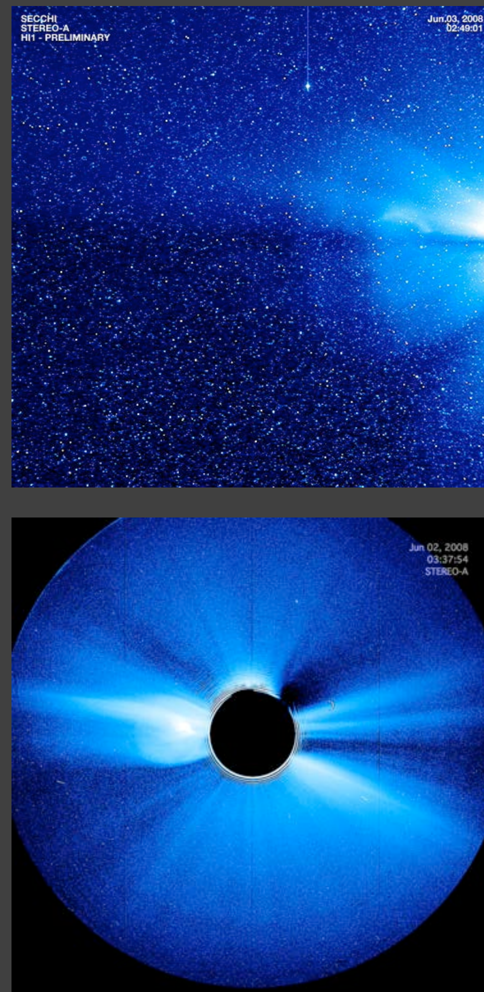
The second three-day workshop focused on identifying technology gaps and future needs for the broad class of science missions identified from the first workshop. This included plenary discussions on the state-of-the-art in small satellite technology as well as a facilitated mission concept design and concurrent engineering session based on the Team-X mission formulation design approach applied at the Jet Propulsion Laboratory. The L5 Sentinel heliophysics concept was used a reference mission for this activity and served as a baseline for additional work performed during the study period. The second workshop also included a public lecture for the community given by Professor Jordi Puig-Suari from California Polytechnic State University at San Luis Obispo on “CubeSat: An Unlikely Success Story”.

The meeting began with a review of the current technology state-of-the-art in propulsion, power, telecom, instrument, and navigation capabilities with assessment of the technology readiness level (TRL) of such systems. While it was recognized that advances move quickly in this field nevertheless areas where critical technology improvements are needed to enable our mission concepts were identified. These included propulsion and proximity operations, lightweight large deployable structures, deep space power and propulsion systems, communication for Direct to Earth (DTE) capabilities as well as for high data rate transmissions, navigation, and instrument miniaturization. Metrics included << 10 arcsec determination and < 20 arcsec control in attitude determination and control, > 100 Mbps two-way telecom, specific impulse thruster systems with Isp near 5000, solar panel arrays capable of > 100 W total power at high efficiency, to name a few. Such capabilities could be developed within academia, industry, and/or government.

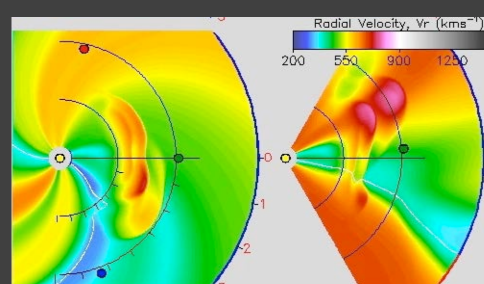
The session continued with a discussion of technology challenges associated with Entry, Descent, and Landing (EDL) of small satellite systems relevant to new mission concepts that might be pursued at Mars, Europa, Titan, and other vistas. Technology advances for lightweight deployable structures were presented, as well as advances in on-board processing technology and approaches for resiliency within the space environment. The study group also heard about new advances in ChipSat and thin-film technologies for lightweight and low ballistic coefficient miniaturized spacecraft.

In addition, a concurrent engineering exercise was held allowing the study group to explore and identify the technical challenges associated with these new mission concepts in a facilitated and structured manner. Rather than performing a mission study by starting with a mission concept and iterating through subsystem designs and trades serially, the concurrent approach allows multiple experts with distinct specialties to work simultaneously to explore the concept design. While our goal was not to complete a full mission study, the outcome was to use the approach to tease-out the technical advances needed for the kinds of missions identified in the first workshop. For this purpose, we chose the Fractionated L5 Space Weather Sentinel mission concept due to its overall complexity.

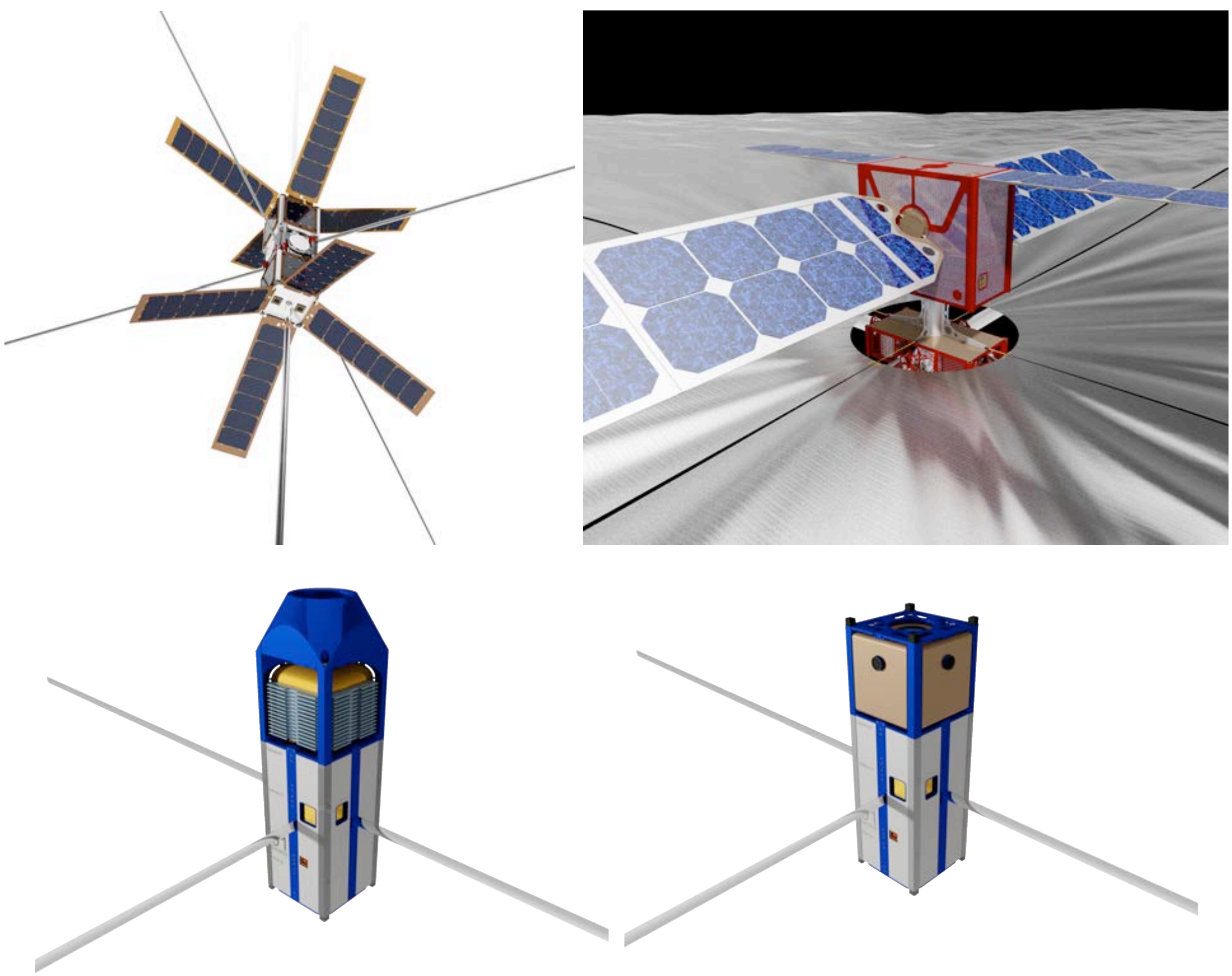
The main product of the exercise was for the subsystem groups to perform analysis leading to mass and power budget estimates, as well as cost. Examining the science objectives and establishing the operational modes the fleet of spacecraft would perform for the L5SWS observations



STEREO white-light imagers demonstrating that CMEs can be seen as they propagate from the Sun to the Earth. Heliophysics Imager (top) and Coronograph (bottom).



Hydrodynamic model run of CME propagating from Sun (white dot) toward Earth (green dot) initiated using observations from STEREO (red and blue dots) achieved this objective. This included analysis for all of the major subsystems including the ACS, command and data handling, power, propulsion, structures and mechanisms, cabling, telecom, and thermal analysis with margins. While the group did not have access to all of the analysis capabilities typically associated with a JPL Team-X concurrent design exercise, there was sufficient experience and engineering judgment to allow the group to close on an assessment of the concept as well as the technical challenges required to achieve the mission concept. Most importantly, the experience also served as a pathfinder for deeper exploration of additional select mission concepts during the post meeting study period. These concepts are highlighted in the engineering section while engineering accurate potential system designs for one concept in each of the three focus areas is briefly illustrated below.



Various spacecraft designs from engineering study for RELIC, L5SWS and ExCSITE

1.4 Outcomes and Recommendations

Establishing a community to identify new scientific discoveries of merit, uniquely enabled by small satellites, was a key outcome of this study. Although technology challenges were identified some near-term concepts are actively being developed and proposed for future mission opportunities. Most of the science concepts created during the study program will require specific technology advancements that must occur over a period of years, and perhaps decades.

Recommendations	Impacts
Beyond LEO SmallSat Science Exploration Program	A means to establish a roadmap and set of scientific objectives tailored specifically to unique small satellite observations in astrophysics, heliophysics, and planetary science. This would include an expansion of the SMEX and mission of opportunity programs to include development of a robust set of small satellite constellation survey missions.
Beyond LEO SmallSat Technology Maturation Program	The means to advance hardware and software technologies, including instruments, to enable long duration and resilient small spacecraft systems compatible with deep space scientific exploration.
Small Spacecraft as Secondaries on All Beyond LEO Missions	Establishing this capability adds value to flagship mission science observation, specifically where measurements are desired in extreme environments or high risk circumstances to the primary, with manageable risk at low cost.
Dedicated SmallSat Launch and Operations Program	A program targeted to this recommendation for beyond LEO small spacecraft systems. This includes investments in ground station capabilities and associated infrastructure to support beyond LEO deployment, telecom, and tracking.
Targeted “Class D” Proposal Opportunities for Beyond LEO SmallSat Missions	The current peer-review process can impede the ability to propose single small satellite missions, as they must compete against higher-class instruments and spacecraft within the same scientific guidelines. This recommendation would support a means to assess how innovative approaches could target specific scientific advances using new platforms.

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The Keck Institute for Space Studies
California Institute of Technology, Pasadena CA
July 2012 and October 2012

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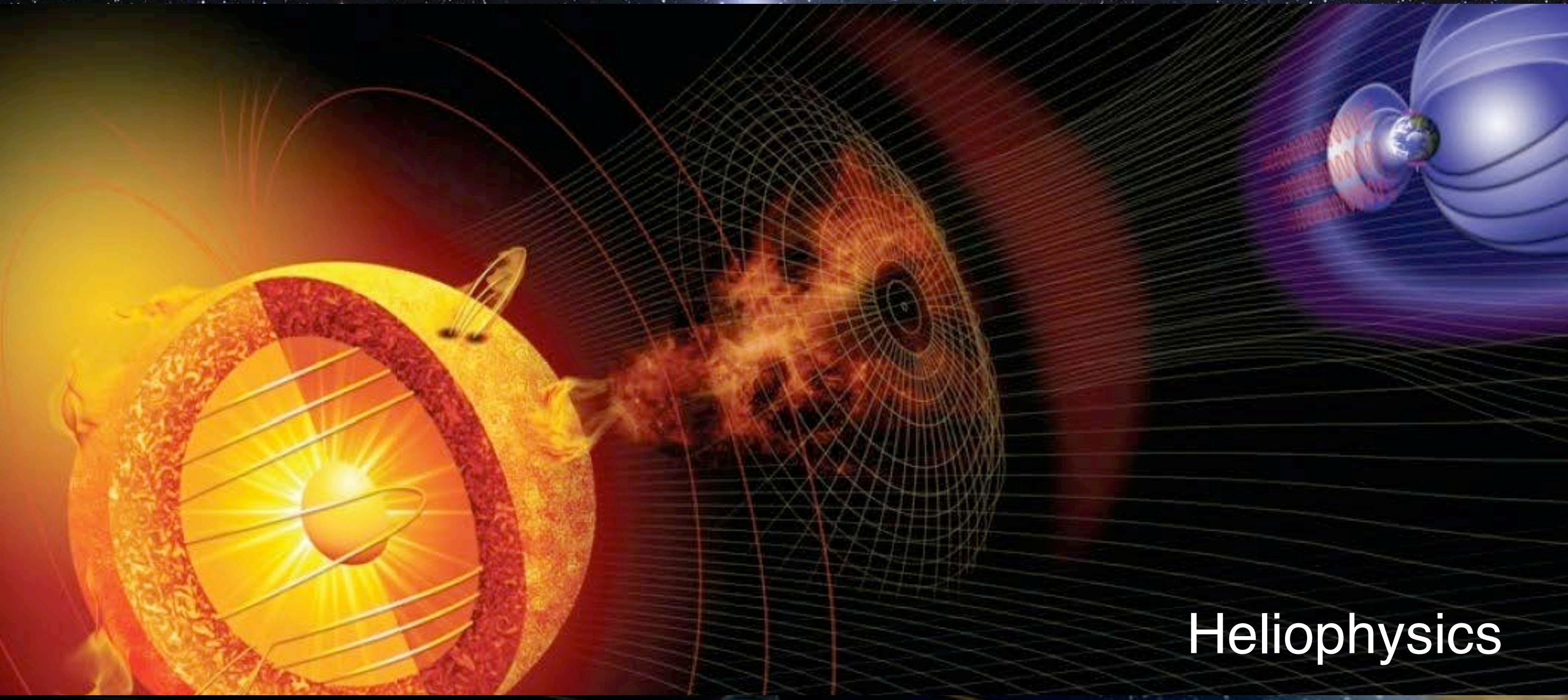
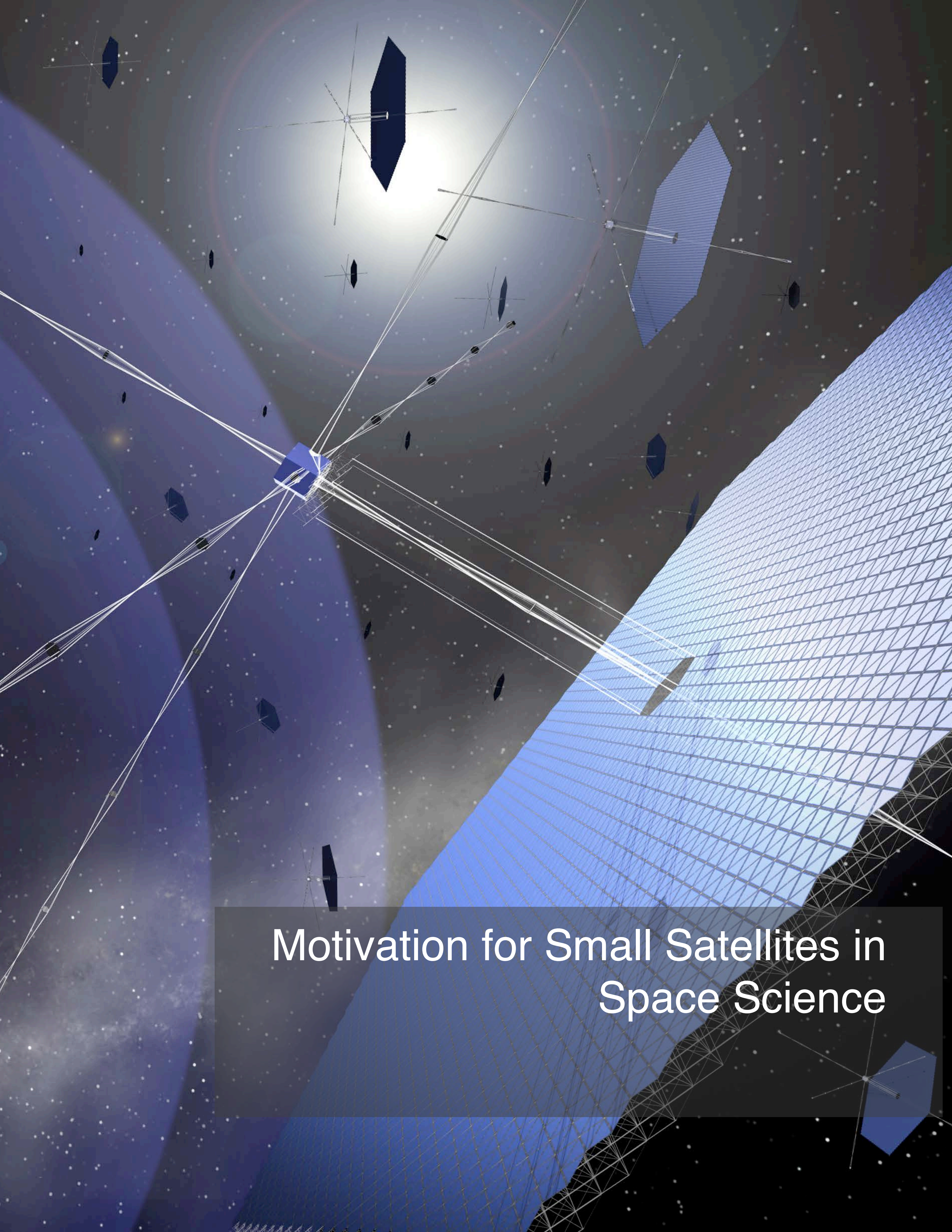
Astrophysics


Heliophysics


Planetary



Motivation for Small Satellites in Space Science

2.1 Understanding Small Spacecraft

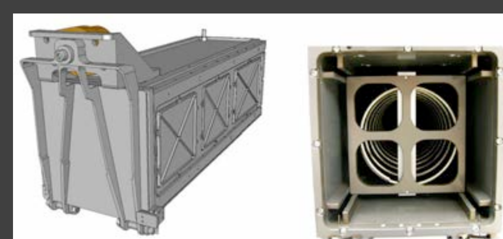
This study focused on small satellites from the ESPA-Class (<180 kg) down to CubeSats (<10 kg) and even ChipSats (<1g). As taxonomy, small satellites have also been characterized as follows: Minisatellite (>100 kg), Microsatellite (10-100 kg), Nanosatellite (1-10 kg), Picosatellite (0.01-1 kg), and Femtosatellite (0.001 – 0.01 kg). Amongst the community of those designing and building systems, however, the terms ESPA, CubeSat, and ChipSat are most prevalent within the definitions given above. A brief overview of this active and rich area is now offered.

Today, the majority of small spacecraft launched, and in development are CubeSat-Class spacecraft. The design specification introduced in 1999 by Bob Twiggs (formerly at Stanford) and Jordi Puig-Suari (Cal Poly San Luis Obispo), defines a 1U CubeSat structure as 10 cm on a side with a mass of no more than 1.33 kg. The introduction of the Poly Picosat Orbital Deployer (P-POD), capable of holding three 1U CubeSats or compatible combinations of them, has enabled frequent access to space for these secondary payloads on a large variety of launch vehicles. It is an enabling capability that has facilitated technology and science experiments from universities, government, and industry through NASA's CubeSat Launch Initiative (CLI), in collaboration with NASA Launch Services (NLS), as well as other launch providers within the DOD and industry. Many of these secondary payload launches are available at no cost.

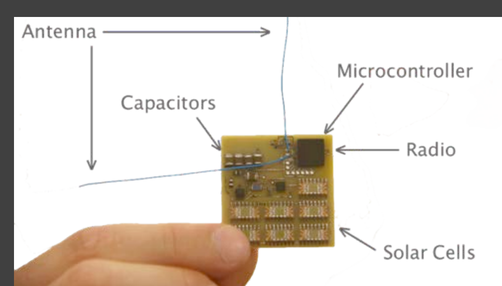
One of the appealing aspects of CubeSats is the rapid sequence from mission conception through spacecraft development, launch, and operations. Typical CubeSat projects can move from idea to realization within 18-24 months. They can also be

EELV Secondary Payload Adapter (ESPA)
(Courtesy MOOG Engineering)

1U CubeSat with dimensions of 10x10x10 cm
(Courtesy Cal Poly San Luis Obispo)



Poly-Picosat Orbital Deployer (P-POD)
(Courtesy Cal Poly San Luis Obispo)

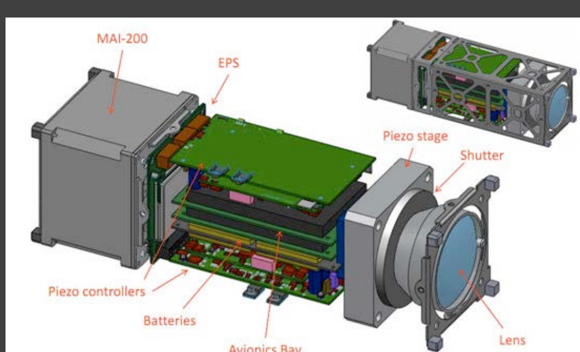


ChipSat Spacecraft Design
(Courtesy Cornell University)

developed for roughly one million US dollars, but many cost substantially less where the lowest known reported cost was thirty thousand dollars. Some systems, however, can cost five to ten million dollars or more. This is all application dependent. The specification, now a defacto standard, is very short defining not only the structural dimensions of 1U and 3U CubeSats, but includes information on testing requirements and waiver processes. The development and approval processes are no less rigorous than for traditional spacecraft – they are simply tailored to this class of platform and mission risk profile. The P-POD enables this as launch safety requirements are defined at the P-POD to launch vehicle interface providing a standard access platform for CubeSats across P-POD compatible launch vehicles. A spring plunger-based mechanism, once a deployment command is received, is used to eject the CubeSat(s) from the P-POD into orbit.

The standard is relatively open regarding the kinds of payloads and components CubeSats may utilize. Most CubeSats are built from COTS components, but as sophistication grows custom, radiation hardened, and military-grade parts are being used for these systems. This is partially in response to concerns regarding reliability of these spacecraft, but also driven by a rapidly growing interest to apply them for military and industrial use as well as technology improvements associated with commercial development of specialized CubeSat components.

The idea of developing CubeSats for space science observations and technology maturation is not new, but the vast majority of systems developed and flown for Earth observations thus far have been in LEO. Examples of existing CubeSat efforts, targeting 2014 launch opportunities, that are synergistic the goals of this study program are ExoplanetSat and INSPIRE. ExoplanetSat, led by MIT, is designed to be the first 3U CubeSat to detect rocky super-Earths by observing bright star crossings using the transit method. While designed using existing technology the system will set



ExoplanetSat Spacecraft CAD
(Courtesy Massachusetts Instiute of Technology)

INSPIRE Beyond LEO Mission Concept
(Courtesy NASA JPL, Caltech)

a precedent for pointing knowledge down to the range of a few arc seconds. INSPIRE, led by JPL, consists of two 3U CubeSats that will be the first to be deployed on an escape trajectory beyond LEO. The mission will assess a variety of technologies important to interplanetary CubeSat development including direct-to-Earth radio communications, tracking, and various electronics subsystems and their tolerance to the space environment.

Space debris is often raised as a concern for these systems in LEO, but there is a 25-year deorbit requirement that must be satisfied (via analysis). Great emphasis is also taken to ensure these systems do not impact performance of the primary spacecraft. This includes a 45-minute radio quiet period post deployment from the P-POD as well as ejection into a different orbital plane from the primary. All of these spacecraft are tracked by the Joint Space Operations Center (JSpOC) providing two-line estimates (TLEs) of spacecraft position made available to the community to plan ground operations for decoding beacon telemetry and for transmit/receive of flight data. Orbit propagation tools are applied for this purpose as well.

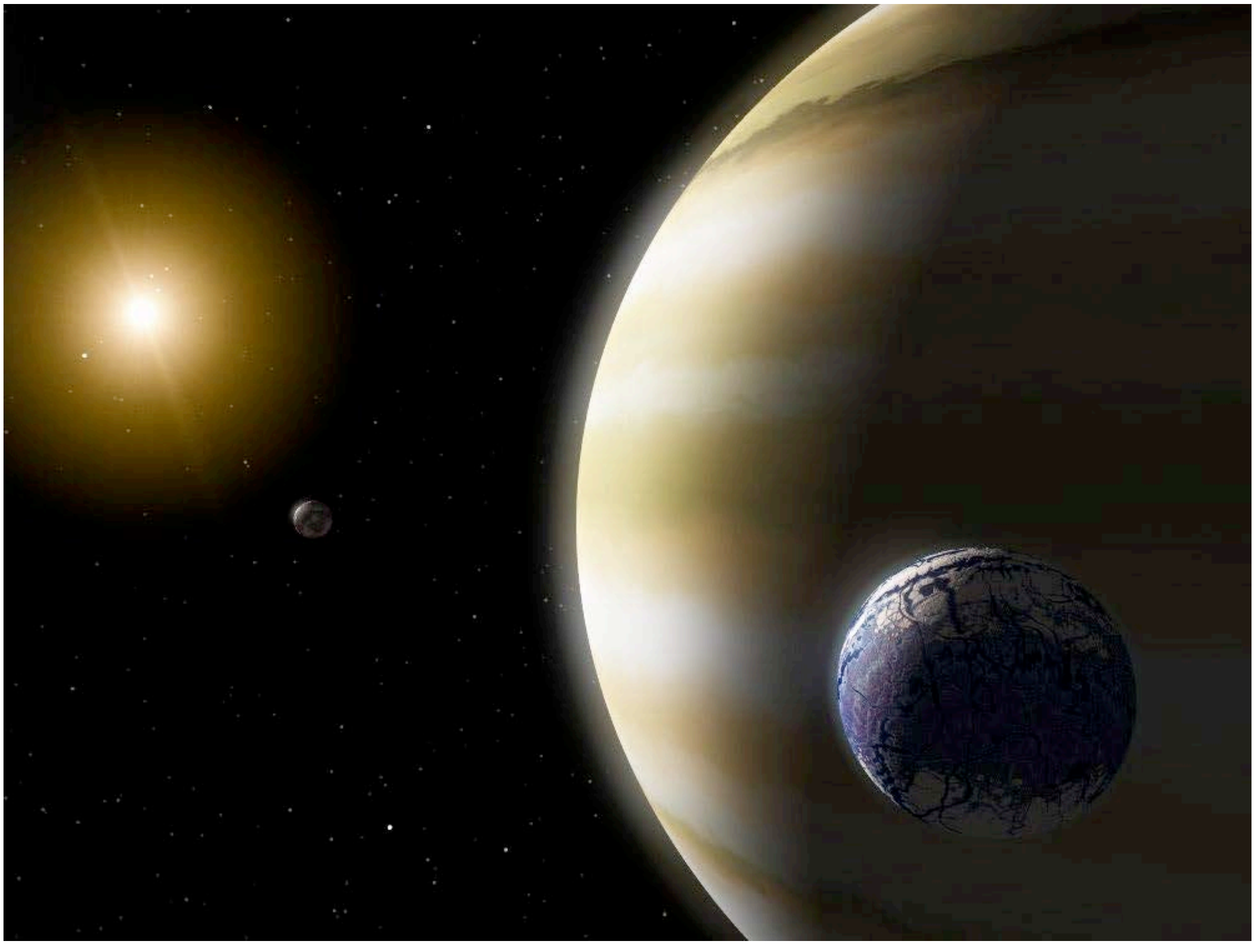
The EELV Secondary Payload Adapter (ESPA) Class systems are enabled by the ESPA-ring, a support structure that can hold up to 6 moderate sized spacecraft as secondary payloads on a host of rockets (as well as a primary up to 6,800 kg). Each slot can support a 181 kg spacecraft and past examples of ESPA usage include the Lunar Crater Observation and Sensing Satellite (LCROSS) among others. The ESPA spacecraft offer many more resources than CubeSats can current provide in terms of payload space, power, telecom, propulsion, and other capabilities. While there are currently fewer launch opportunities available when compared to CubeSat systems that number is steadily increasing. The ESPA-Class spacecraft are appealing as their size can easily support large aperture systems and with the introduction of the ESPA-ring multiple systems can be deployed simultaneously, or in a staged sequence.

ESPA-Class spacecraft are not limited to ESPA-ring deployment systems. Numerous vendors now provide rideshare capabilities for these spacecraft on custom designed multiple payload adaptors. These systems can support a variety of spacecraft and many of these systems also have propulsion and navigation capabilities providing a means of directing the payloads to specific orbits and trajectories of interest. There is a standard the defines ESPA-Class systems as well as a set of guidelines that identifies rideshare capabilities to get to space, known as ESPA Standard Services, should one pursue launch opportunities via the Space Test Program (STP). Similar to the NASA CLI, this is one mechanism to get an ESPA-Class spacecraft to space at no cost through competition – usually the Space Evaluation Research Board or SERB. Finally, a variant of the ESPA ring in development, called ESPA Grande, has 5 slots that can support payloads up to 600 kg each. Furthermore, industry is also developing accommodations for ESPA to support CubeSat deployment.

ChipSats and Thin-Film Spacecraft/Lander/Rovers (TF SLRs) are an experimental technology exploring what can be achieved using postage-stamp to handkerchief-sized spacecraft at the gram to milligram scale. The appeal of these systems are that they are easy to fabricate, very lightweight and can be deployed in significant numbers enabling swarms of spacecraft to make multipoint distributed physics measurements. While larger systems, even CubeSats, have the potential to carry propulsion systems ChipSats and TF-SLRs would generally depend on the surrounding environment, such as the solar wind or solar sailing, for motion, although the use of microfluidic based propulsion system for TF-SLRs is being explored. Even though power and communication capabilities would be very limited (although larger TF-SLR devices are expected to have CubeSat-like capabilities), they could explore environments where extreme conditions exist as ChipsSats can be dispersed in sufficient numbers that some percentage of failures would be tolerable in achieving unique science measurements.

Printed circuit board ChipSat development prototypes have been developed to TRL-8 and deployed as test articles on the International Space Station and for release by the KickSat CubeSat in LEO. Hybrid Si/GaAs ChipSats and TF-SLR prototypes have also been developed to TRL-8 with TF-SLRs scheduled for flight in LEO and GTO within 2014. While regarded as a burgeoning research area they are taking advantage of recent advances in micro electrical mechanical systems (MEMS) electronics, process engineering, RF ASIC design, hybrid printed electronics and other technologies related to precision small scale electronics. Cornell University, and University of Strathclyde in the UK have been exploring ChipSat-based spacecraft systems, while JA / PocketSpacecraft.com has performed work in that regime as well as TF-SLRs, among others.

New technologies, particularly in the area of instruments, telecom, navigation and propulsion systems, will continue to open new possibilities for small satellite science observations. Improvements in low cost, highly reliable, available, and space qualifiable electronics are also driving this area. Nevertheless, additional (in some cases significant) technology advances are still needed to enable revolutionary space science from these systems; these advancements, as well as the challenges to overcome, are also addressed throughout this report.



2.2 A New Path Toward Space Exploration

The study group considered the future plans outlined in the Decadal Surveys for Astrophysics, Heliophysics, and Planetary Science. The Decadal missions proposed did not consider small satellites so this served as a challenge to design equally significant science observations enabled by small satellites. Our discussions revealed a variety of science opportunities that are targeted to, and enabled by, small platforms along with others that are complementary and compatible with the existing Decadal Survey scientific objectives. A critical challenge to the study group was to avoid identifying measurements just for the sake of satisfying the known capabilities of small platforms, but rather to identify ways to approach decadal science with new observational strategies that could also open pathways to future exploration concepts of critical importance to the scientific community.

Naturally, a significant factor in exploring small satellites as a new approach involves benefits in size, weight, and power (SWAP), as well as cost, and time to development from conception through launch. Fundamentally all of these parameters can be optimized when compared to traditional spacecraft missions, but this can only be true for targeted science observations. Physical limitations for certain space science measurements where, for example large optics are required, would not be suitable for small spacecraft and the study group was careful to recognize that there are regimes of science exploration that can only be performed with large missions. The point here, however, is that new relevant science can be enabled by the use of small platforms, and in many cases the benefits of size reduction can enable first of a kind discoveries once one thinks creatively and beyond the typical way of approaching a scientific measurement.

In this regard, an important motivation for this study was to identify important science that would explore fundamental questions, in regimes not previously considered. Many of these questions required new observation approaches such as spacecraft constellations, and/or continuous all-sky observing coverage, or sensors that are in-situ and/or in extreme environments that are simply not feasible via stand-alone large and expensive missions. The study group clearly found that a wide set of credible missions do exist that are uniquely suited to smaller platforms. Furthermore, great benefits can be realized through a new approach to space science discovery that can incorporate collaborative science with traditional large missions.

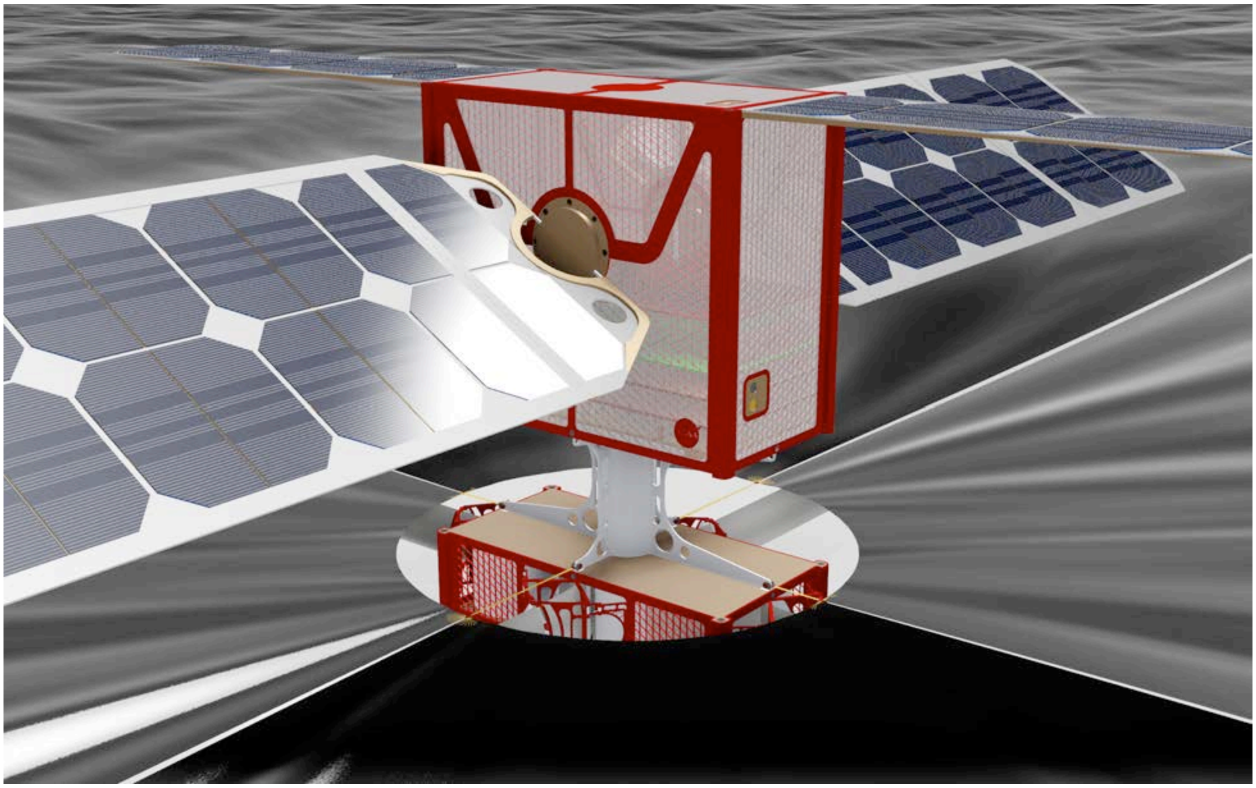
2.3 Opportunities, Risks, and Rewards

One common theme of the recent decadal surveys has been an assessment of risk, specifically cost and implementation risk, of the science proposed. Small satellite solutions, in regimes where practical science has been identified, would provide rapid and affordable means to make important scientific breakthroughs within cost constrained environments. Technology advancements have also led to high reliability system components that could be rapidly integrated into complex systems. Furthermore, the state of the art is such that this could be achieved through educational programs at universities, or within government agencies, and industry, where highly creative individuals are creating new opportunities for students to gain direct experience with flight systems followed by immediate placement into the workforce. These systems would also provide a means for seasoned professionals to reinvigorate their creativity as new approaches are conceived for these non-traditional platforms.

There are risks to this approach, typically identified within the areas of long-term reliability and launch opportunities. Nevertheless, all space explorations contain some risk that must be managed, yet small spacecraft systems provide the opportunity to characterize nearly all of the known risks as the systems are much more focused and manageable than traditional large spacecraft missions with numerous objectives. This is not to say that traditional large missions with specific goals would be supplanted, but opportunities exist to fully manage risk via alternative mechanisms for highly focused and low-cost exploration on small satellite platforms. Opportunities also exist for small satellites to fly with larger missions as secondary spacecraft deployed in transit or to enhance primary observations. This is not a new concept, but introducing secondary small satellites with primary flagship missions, as a regular mission capability, is a new opportunity recommended within this report.

Finally, there exists a range of important scientific observations and discoveries to be made that can be uniquely performed from small platforms. Risks can be managed via deployment of multiple systems as well as through regular and low-cost access to space. Small satellite platforms can complement larger missions either through collaborative observations or through important secondary science.

Study Program Goals and Objectives



3.1 Small Satellites for Revolutionary Space Science: Why Now?

The fundamental objective of this study program was to identify and motivate new scientific advances enabled by the small satellite platform to advance our knowledge in space science. Specific discipline areas covered astrophysics, heliophysics, and planetary science. Additional goals included identifying the technological advances necessary to achieve such missions while establishing a community to lead further development of publishable scientific and technological priorities necessary to achieve a new generation of space missions based on small satellite capabilities.

The scientific community is eager to explore the solar system and beyond, but budget limitations and the lack of flight opportunities are starting to restrict the capability to pursue fundamental questions in these regimes in a timely fashion. In the current paradigm, the ability to pursue new and/or needed follow-on observations and measurements to expand our knowledge will require the vast majority of a scientist's career, the opportunities to do so are extremely limited, and the cost/risk posture of current mission concept design does not support the innovations needed to address the fundamental scientific need for multipoint and frequent measurements to properly characterize space phenomenology and/or the observations truly desired. Indeed, our current posture is also impacting the ability to grow the next generation of scientific explorers that will not tolerate working on a single project that may require decades of development with the risk of potential technical or cost failure where the hope of a timely replacement mission may be undetermined or unlikely.

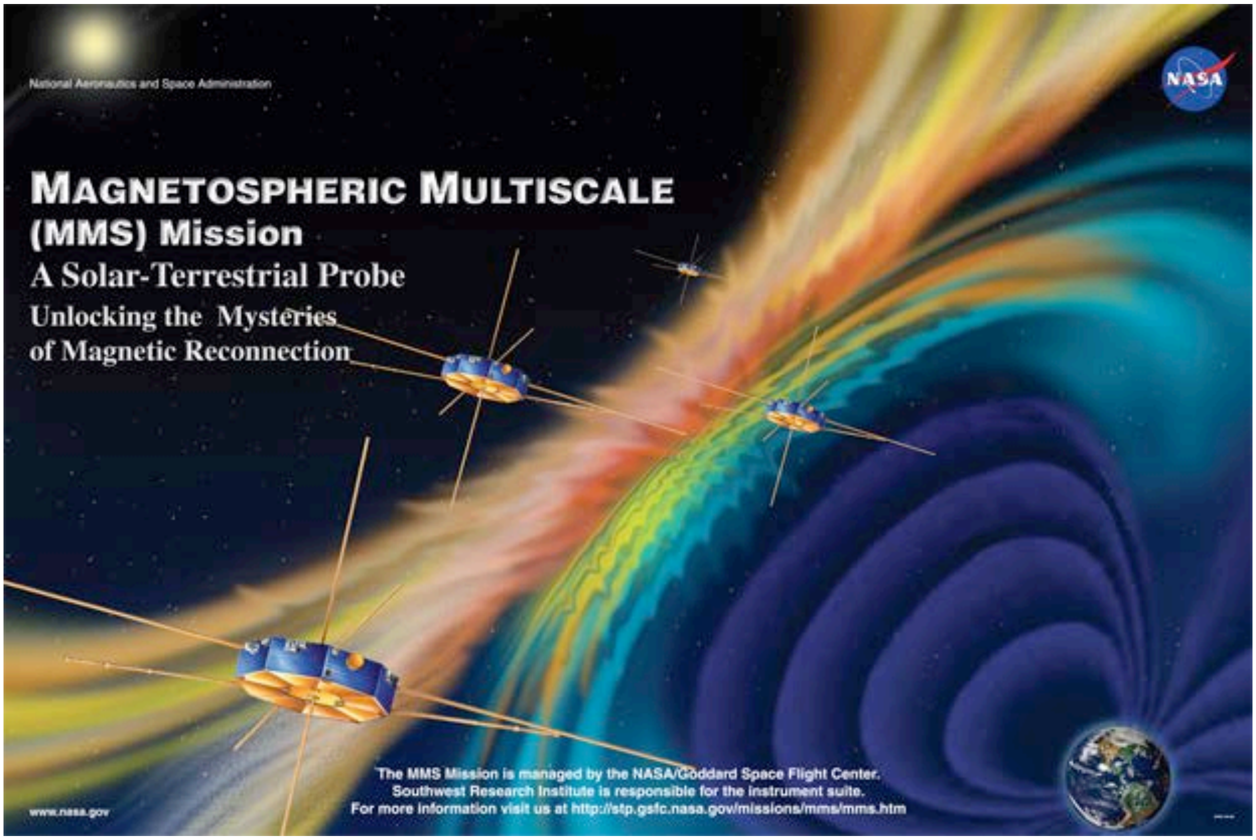
There is still an important need for flagship missions that can make observations that are only capable from large platforms and large investments. Nevertheless, technology advancements, the need for specialized, targeted, and higher risk observations, as well as regimes of scientific exploration that can not be made by a single spacecraft now demand that new approaches be explored in space science research. There truly are critical scientific questions to explore that are not only enabled by smaller spacecraft, but that can only be answered using such platforms. Now, as the scientific community continues to expand their range of inquiry, and knowledge about the capabilities of these systems, measurements heretofore unknown to us are coming into view and opening a vast array of exciting observations that will be transformative in how space science research can be conducted in the years to come. The work of this team represents a first organized effort to open this new path to the vast majority of new, and experienced, explorers that realize the potential for new discoveries ahead based on small satellite systems.

3.2 Motivating the Disciplines of Study

The focus areas of Astrophysics, Heliophysics, and Planetary Science (including small bodies and Near Earth Objects) were chosen for specific reasons. They align with the current exploration programs within NASA, and other international space agencies, where the vast majority of space science exploration is managed and performed. More importantly, however, each area brings unique challenges as one explores the revolutionary observations that are uniquely enabled by small spacecraft.

In astrophysics the potential exists to perform continuous all-sky surveys and to make measurements in regions of the electromagnetic spectrum that require multi-point observations that cannot be performed from ground-based systems, such as very low-frequency radio observations. Furthermore, the potential exists to deploy distributed large synthetic aperture systems utilizing small satellites enabling maintenance via replacement of satellites periodically over time. Incremental development and deployment reduces risk, supports enhancements and upgrades, and with appropriate technology development in information systems and distributed processing allows for high resolution measurements based on structures larger than what can be deployed using a single spacecraft.

The motivation in heliophysics is very similar as this is a discipline that demands long-term, distributed, and multi-point observations to fully characterize the Sun-Earth Solar system interactions. Furthermore, many of the required instruments are small, low-to-moderate power, and are compatible with small spacecraft system designs. The



potential exists here, as well, to deploy multiple spacecraft to vastly increase the number of observations. This is not a new approach for the heliophysics community. Indeed, missions such as the Magnetospheric Multiscale (MMS) mission have flown four identical spacecraft (3.5m x 1.5m major dimensions) for distributed magnetic field measurements. THEMIS has flown five spacecraft to identify the process leading to Aurora eruptions. Yet even in these cases the opportunity exists to expand to constellations of hundreds of dedicated observers carrying magnetometers, particle detectors, electric field instruments, and others, to explore a broader region of space.

For planetary science the number of opportunities for exploration is small so the addition of small satellites as secondary payloads can significantly expand scientific study at very reasonable cost. Depending on the propulsion mechanism selected opportunities can exist for stand-alone small spacecraft missions, but in this regime excess launch performance can often accommodate additional spacecraft coupled to the primary spacecraft, the launch vehicle, or both. Challenges exist in survivability both thermally and in the radiation environment, but in many instances the ability to utilize multiple small spacecraft can allow for short-term measurements in extreme environments where the risk would exceed the tolerance of a large flagship-class mission. Opportunity, and risk mitigation, can also take the form of multiple spacecraft

performing new kinds of proximity operations around small bodies and near Earth objects, as well as sacrificial missions consisting of impactors with partner spacecraft that can observe and record results. The motivation here is that exploration in this regime should utilize as many observing capabilities as possible given the rarity of visits to these vistas.

While the concept studies in these areas emphasized revolutionary scientific and technology advances for small satellite space science, the primary focus addressed mission concepts that are uniquely suited to these platforms. There are appropriate roles for traditional large spacecraft that will not be served by small satellites, but there is also a great and growing level of community creativity regarding the next generation of exploration missions that can be achieved uniquely via this platform. For this reason, the study group explored concepts that extend from the near term (less than five years) to the far term (more than twenty years).

Decadal Survey Reference	Survey Report Comments Suggesting New Approaches
From the Decadal Survey on Astronomy and Astrophysics report, “2020 Vision: An Overview of New Worlds, New Horizons in Astronomy and Astrophysics”	Small (SMEX) and medium-size (MIDEX) Explorer missions, developed and launched on few-year timescales, allow rapid responses to new discoveries and provide versatility and high science returns. However, the goal of deploying a small and medium astrophysics mission every other year is not being met.
From the Decadal Survey on Heliophysics report, “Solar and Space Physics: A Science for a Technological Society”	The (small satellite) projects have been deemed by peer review to have well-defined, important science objectives and to provide unique datasets. All … carry the promise of precedent-setting measurements. (They) provide a unique platform for technological innovation where technical readiness can be developed to levels appropriate for application on larger spacecraft.
From the Decadal Survey on Planetary Science report, “Vision and Voyages for Planetary Science in the Decade 2013-2022”	A significant concern with the current planetary exploration technology program is the apparent lack of innovation at the front end of the development pipeline. It is equally important that there be an ongoing, robust, stable technology development program that is aimed at the missions of the future, especially those missions that have great potential for discovery and are not within existing technology capabilities. The deep-rooted motives underlying the planetary sciences address issues of profound importance that have been pondered by scientists and non-scientists alike for centuries. They cannot be fully addressed by a single spacecraft mission or series of telescopic observations

3.3 Short-Term and Long-Term Study Goals

The concepts identified in this study were intentionally focused to open a broad series of investigations using a variety of techniques amenable to small spacecraft design. In the short-term, this study aimed to critically question and assess if small spacecraft could make fundamental contributions to space science research either as stand-alone systems or in collaboration with traditional mission design. Driven by the trends in scientific observation goals from guiding documents such as the decadal surveys, and our own creativity, it was clear that relevant and significant discoveries could be uniquely enabled by small spacecraft platforms. As a result, through scientific and engineering analysis across two study periods, a major short-term goal of our group was to establish and grow the community of scientists that would consider missions using small satellites as well as defining a series of recommendations that would support and enable future mission concept development.

In the long-term, the study group hopes to motivate a new line of scientific inquiry within the space science community and new approaches to exploration that challenge traditional methods of beyond LEO observations in a scientifically justifiable and technologically achievable way. The team also intends to set a new path toward resolving the challenges outlined above regarding risk, time, and growth of the scientific community. Fundamentally, this new approach can and should permit a larger group of explorers to participate in answering the fundamental questions of our local space environment and the universe at large where small satellites provide relevant and key contributions to the advancement of knowledge and fundamental understanding of the most challenging open questions in space science.

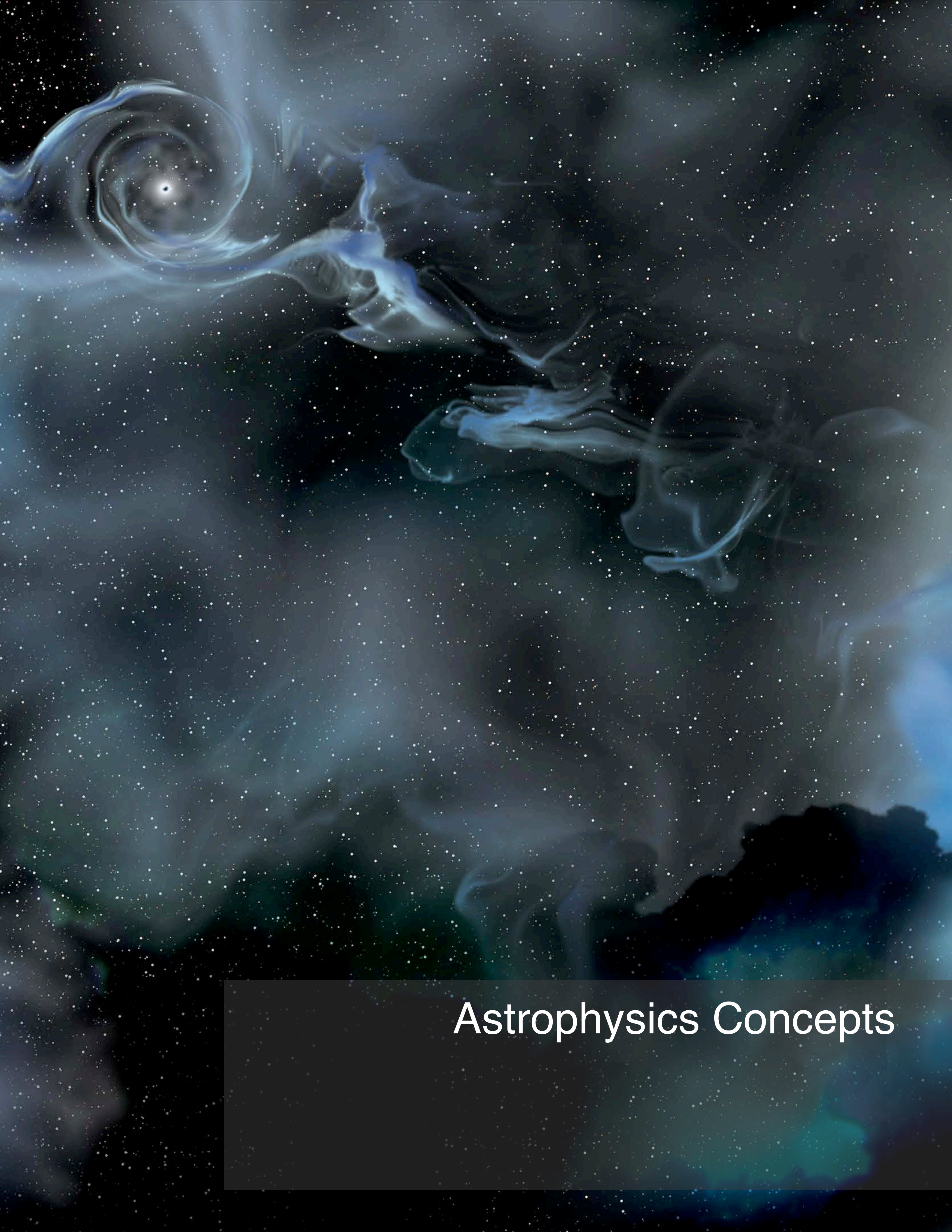
Science Driven Mission Concepts

4.1 Small Satellites for Novel Space Science Observations

The study team brainstormed many scientific concepts where small satellites could make a scientifically significant discovery suited specifically for this platform. In the end, each subgroup narrowed down to three topics for deeper investigation at the level of a basic concept definition. As will be seen in the engineering section of the report, subsets of these topics were assessed via a more detailed design analysis to serve as a starting point for mission definition and exploration. This work continued amongst the study group members during the study periods in between and following the formal close of the workshops.

Fundamentally, the topics explored by discipline area could be loosely characterized as targeting close proximity operations in planetary science, all sky surveys across multiple wavelengths in astrophysics, and multipoint distributed physics measurements in heliophysics. While the concept definition topics are explored here other candidate concepts were also discussed. These included exoplanet constellations that would look for faint transients beyond the visibility of missions such as Kepler; all sky survey constellation missions to measure the broadband spectral energy distribution; large synoptic survey telescope (style) observations in the infrared to search for very distant and bright quasars including the time history of black hole growth; or cooperative observations in the UV, X-ray, and IR. Other discussions explored surface processes and habitability of icy moons, Venus atmospheric science, Titan lake explorers, and the search for exoplanets around the brightest stars via small satellite micro lensing techniques, as well as asteroid and small body seismology.

In addition, a common theme emerged as the teams were challenged to look at new observations, in new ways, given the capabilities of small satellites. We concluded there are numerous investigations that could be pursued that complement, extend, or redefine how space science observations have or could be made. Relevant and significant science can be performed where the goal now is to accept the challenges associated with broadening the paradigm of how typical observations are conceived and performed when compared to traditional approaches.



Astrophysics Concepts

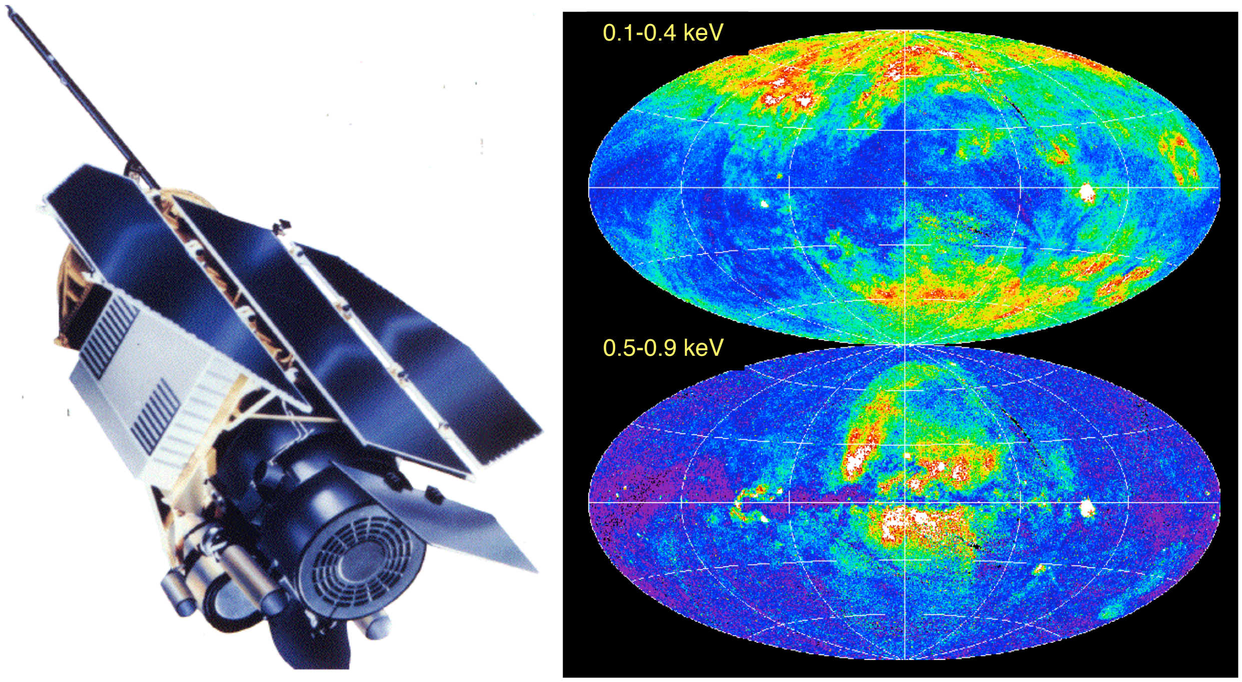
4.2 Astrophysics

The most common argument against small satellite based astronomy is that large apertures, cryogenic detectors, and high pointing stability are required for deep space observations and that these are not compatible with small systems. Within the astrophysics subgroup, however, were identified a number of observations that collectively spanned a large portion of the electromagnetic spectrum where important discoveries are yet to be made. In fact we concluded there exist various observations that have not been made simply because they were not compatible with the typical large telescope spacecraft model. In particular, our process identified various survey missions that can utilize relatively simple instruments where constellations of small spacecraft from LEO, Earth trailing, or other orbits, could address and resolve open questions in space astronomy and astrophysics.

In the following, we explore the SoftX mission concept that would utilize a single or small set of 3U or 6U CubeSats to measure the thermodynamic parameters of the local hot bubble (and galactic halo) to better understand the history and evolution of our local environment. With the ability to scan the entire sky many secondary science objectives can also be met involving energetics, supernova impacts on the interstellar medium, and it would inform star formation feedback models for galaxy evolution. It would not only build upon the successful broad band maps produced by the ROSAT mission, but would also produce sky maps in the narrow energy bands associated with specific elements to help characterize the origin of the soft X-ray background. A new monolithic CMOS detector, collimators, and micro-cryocoolers enable this observation.

The Relic concept explores low frequency radio astronomy using aperture synthesis of many small spacecraft, flying in formation, to understand energy transport from black holes to the intergalactic medium. The objective here is to image double-lobed active galaxies at frequencies well below 30 MHz using aperture synthesis. This observatory could be fielded at the Earth-Sun L2 point, an Earth trailing drift away orbit, or in a low gravity gradient environment in lunar proximity space. The spacecraft, mission, and technology challenges are studied in the engineering section of this report.

We also describe UVIP-UV Reionization Probe designed to understand the source and mechanism of reionization in the early universe. As another constellation mission concept it would explore the properties of “young” local analogues to high redshift galaxies and the conditions that control the escape of ionizing photons to understand how this led to reionization. Such observations could be coordinated with larger missions, such as LSST, adding additional science related to massive star formation and evolution, tidal disruption events and others via UV coarse spectral imaging.



ROSAT Spacecraft (1990-1999) and Soft X-Ray Images (Image Credit: Max-Planck Institute)

4.2.1 SoftX: Measuring the Local Hot Bubble

The scientific objective of the SoftX mission is to perform an all-sky survey to measure the low energy diffuse background from the interstellar medium in the soft X-ray band (the local hot bubble).

One of the first discoveries of X-ray astronomy was a diffuse glow of emission from all directions in the sky - the X-ray background (XRB). Above 2 keV, this emission is dominated by active galactic nuclei and was finally resolved by the Chandra X-ray observatory. Below 1 keV, however, the emission is mostly thermal with a complex spatial morphology that defies easy interpretation. Prior to the launch of ROSAT, it was believed that the emission from the XRB below 1 keV was the result of emission from the local hot bubble (a region within about 100 pc of the Sun filled with 10^6 K gas - 1/4 keV RASS image shown above) and emission from the large scale galactic halo of the Milky Way. Since the discovery of Solar Wind Charge Exchange (SWCX) emission from a comet in the mid 90s, the situation has become less clear, and it is now argued that some or all of the emission (particularly in the 1/4 keV band) comes from SWCX within 100 AU of the Sun. Emission from all three components (SWCX, local hot bubble, and the halo) are likely to be significant, but the spatial and spectral decomposition of these components is unknown.

A CubeSat mission flying a mechanically collimated CMOS soft X-ray spectrometer could provide significant scientific gains in our understanding of the Solar heliosphere, the local hot bubble, and the galactic halo. We would fly two monolithic CMOS sensors each with a 5x5 degree collimator with the FOVs of the two instruments offset by several degrees. The CubeSats would continuously scan the sky, in a sun-sync orbit that allows them to look anti-nadar (away from the Earth at 90 degrees to the sun) allowing them to scan great circles being viewed by 1 degree each day. The two sensors would view the same region of the sky separated by several days. The scientific goals of this mission concept would be:

1. To characterize temporal variability in the SWCX emission from the heliopause. Variations in the velocity and density of the Solar wind sound create temporal variations in the emission on timescales of days. This variability will also separate SWCX emission from that of the local hot bubble.

2. Resolve emission lines of O VII, O VIII, N VI, N VII, C V, and C VI to determine the temperature, ionization state, and abundance of the emission. Suzaku observed the soft X-ray emission along selected lines of sight. Soft-X would be able to do this all over the sky. Depending on the observation, and conditions, one could detect 5-20,000 counts per day in the bright lines (O and C). Note also that with high-speed readout and thin optical blocking filters we should go below 0.2 keV with good response.

3. Map the spatial variations of these emission lines along difference LOS through the heliopause (for the SWCX) and in the galaxy (for the local hot bubble and halo) to constrain the geometries and thermodynamic states of the plasma.

4. Search for the high ionization emission states of C and O indicative of CX emission. This would allow the clean separation of the components and to conclusively determine the contribution of SWCX.

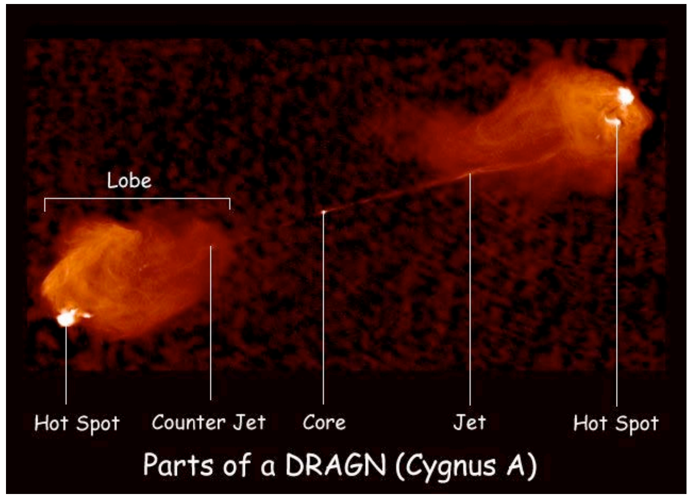
5. Look for shadows due to absorption by intervening molecular clouds in each of the emission lines. This would constrain the locality of the emission regions.

6. Removing the SWCX and accurately determining the temperature and emissivity of the local hot bubble would provide important constraints on the energy balance in the local interstellar medium (ISM) and dynamics of the blowout of supernova (SN) driven superbubbles as they emerge from the Galactic plane, the star formation history of the local stellar environment, and the relationship between this hot phase and the warm/cold phases of the ISM.

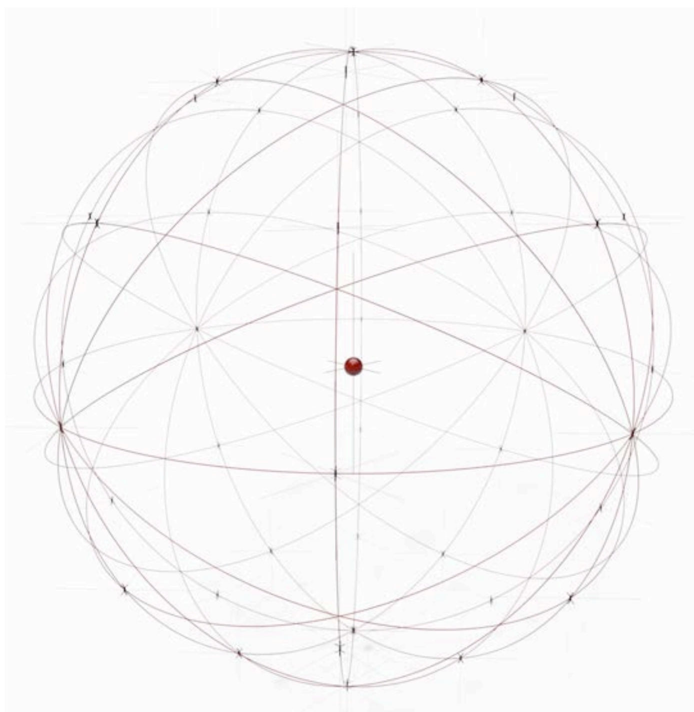
4.2.2 Relic: Understanding Energy Transport from Black Holes

The scientific objective of the Relic mission is to understand energy transport from black holes to the intergalactic medium.

The very low frequency radio regime (~5 MHz) is inaccessible on the ground and in the near Earth environment. However it is an extremely interesting band for probing the processes of particle acceleration in active galaxies. At this low frequency, the radio receivers are simple dipole antennas. The idea of RELIC is to develop a constellation of nano-satellites each containing a single dipole antenna and low frequency receiver and to fly these in a loose formation to form an interferometric array (synthetic aperture) with sufficient angular resolution and sensitivity to map the low frequency radio emission from distant galaxies and map the sites of particle acceleration to help understand the physical processes that are taking place in these active galactic nuclei.



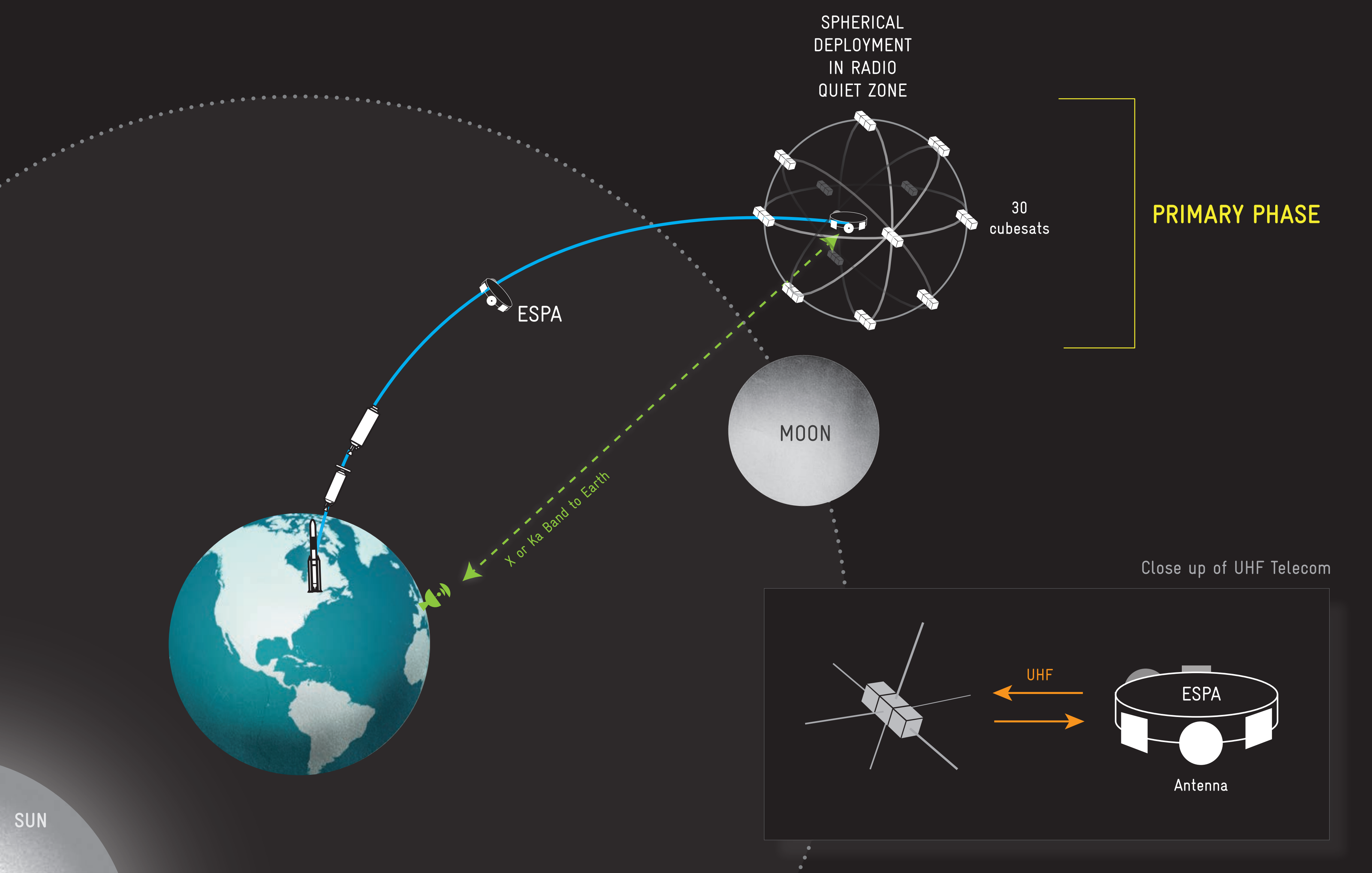
Double Radio Active Galatic Nuclei



Rendering of NanoSat Observing Constellation

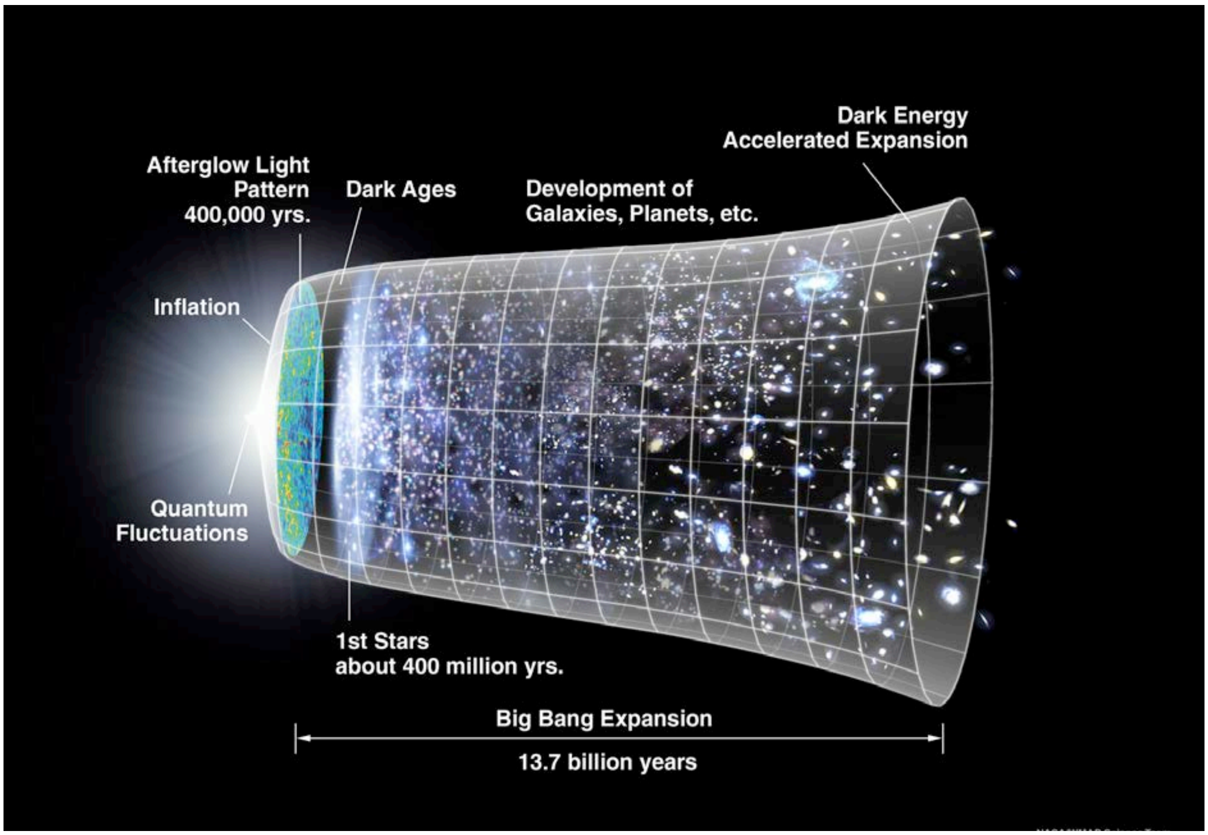
An estimate is that the constellation consists of ~100 CubeSats in a spherical formation with ~10 cm station keeping (small compared to the wavelength of the radio signal at 5 MHz). Each satellite transmits to a larger host spacecraft ('mothership') the signals it receives with an accurate time stamp that is synchronized to all of the other antennas allowing the host to cross correlate the signals and generate the desired images. The constellation needs to be located far from the Earth and its magnetic field, so a drift away orbit is one desired configuration.

RELIC



SPACECRAFT FORMATION	30 *CUBESATS*	*SPHERICAL CONSTELLATION*	**DEPLOYMENT TRAJECTORY**	*EARTH ESCAPE*	*cis-lunar space*	**MISSION LIFETIME GOAL**	*CONTINUOUS*

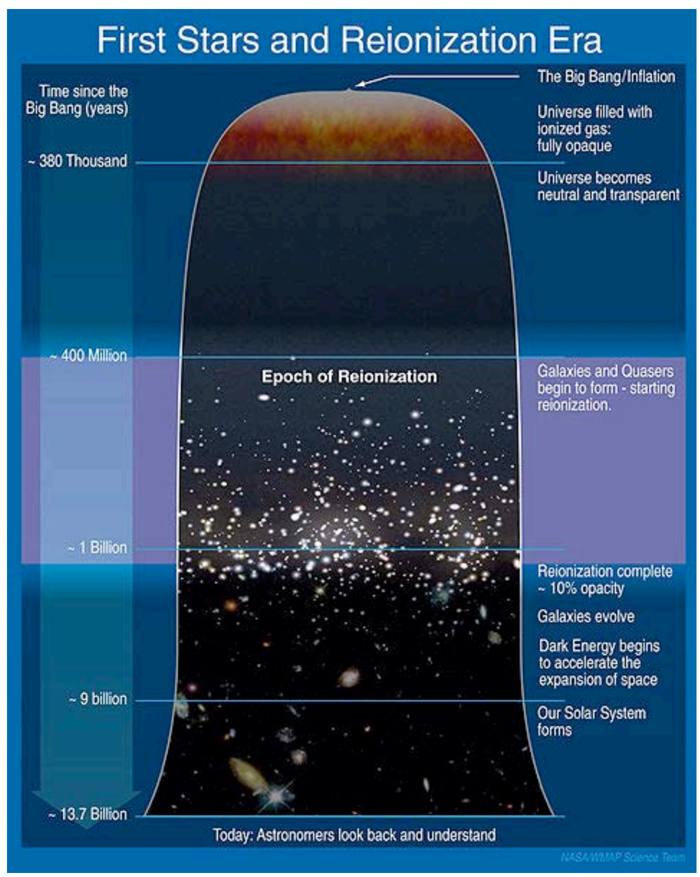
This also minimizes the disturbance torques acting on the satellites and reduces the propulsion needed for station keeping. The mothership is a much larger and more power demanding satellite that not only receives the signals from the constellation of CubeSats, but also performs the signal processing and direct to Earth transmissions.



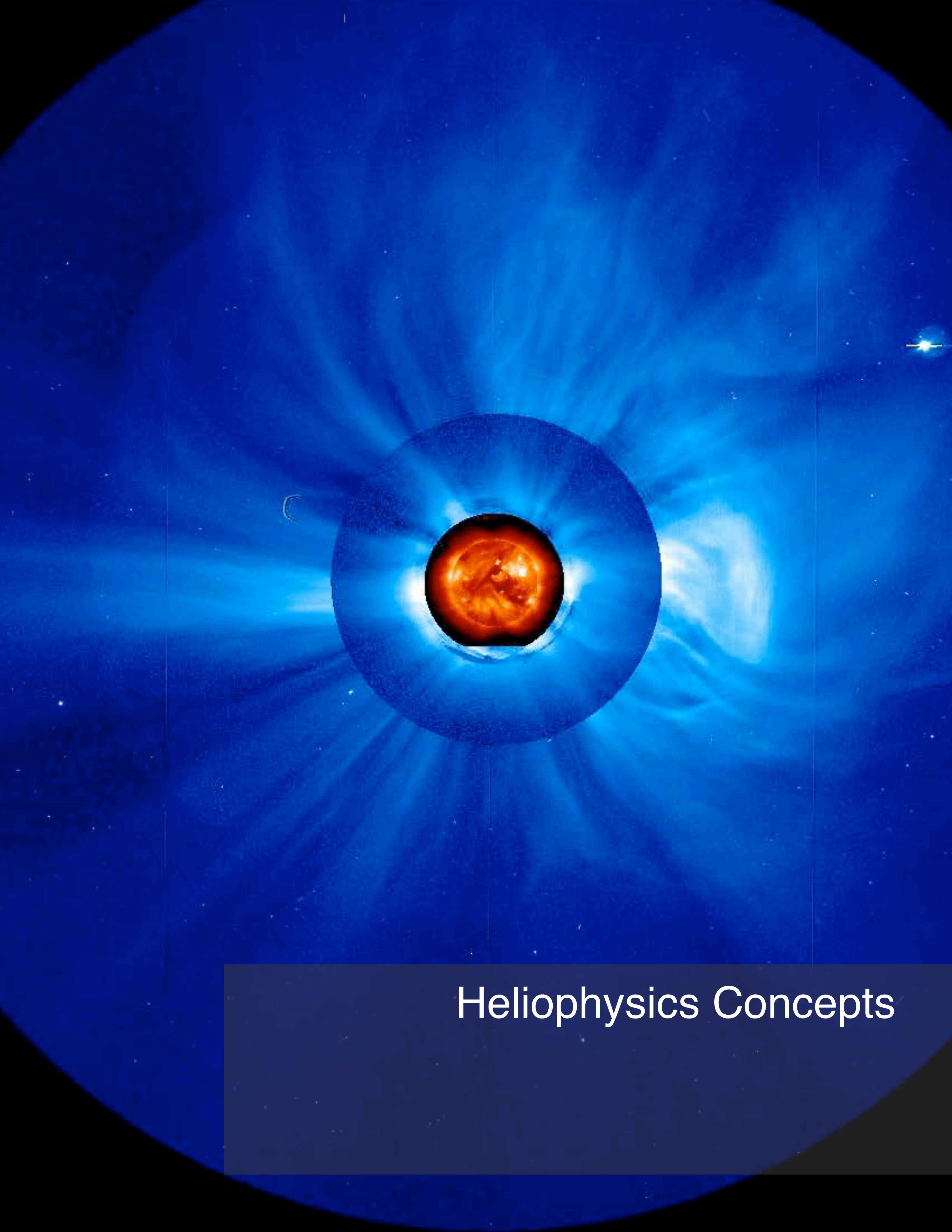
4.2.3 UVIP-UV Re-ionization Probe: Exploring the Early Universe

Following the Big Bang, and prior to recombination, the Universe was fully ionized when the protons and electrons combined to form hydrogen and the Universe became neutral and dark. Eventually, the first stars and galaxies formed and the Dark Age ended. UV light from these first bright objects disassociated the Hydrogen atoms to recognize the universe. This is the state of most of the Universe today, fully ionized and very low density making it essentially transparent to electromagnetic radiation and thus enabling us to see very distant objects. The process by which the early universe became re-ionized is not very well understood yet a leading candidate is the UV light from young star-forming galaxies that escapes (or leaks) from these galaxies and disassociates the local hydrogen atoms in an ever-expanding volume around these galaxies until eventually most of the Universe is recognized.

The UVIP is a small fleet of small satellites (larger than CubeSats, ~1x1x1 meter) with UV telescopes that will survey the local region looking for young actively star forming galaxies that are analogues of the first galaxies. These observations must be done from space since the Earth's atmosphere absorbs the UV radiation of interest (energetic enough to ionize Hydrogen). Once such galaxies are found, UVIP satellites will study these in more detail to measure the fraction of the UV light that escapes the galaxy. This escape fraction is the critical parameter that is needed to determine whether young star forming galaxies could have been responsible for the era of re-ionization. Finding local analogue UV galaxies can be accomplished with a few relatively small aperture UV telescopes (15-25 cm diameter) that scan large solid angles and map the sky. Once candidates are found, these same telescopes can stare at the galaxies long enough to obtain high-resolution images mapping the UV emission and especially the relatively low surface brightness associated with escaping UV radiation. UV sensitive cameras could record these images where they would be returned to the Earth for analysis.



The UVIP-UV re-ionization probe mission concept would explore discovery and characterization of nearby young galaxies, as analogs of the early universe to study how UV radiation produced in these galaxies can escape into the surrounding inter galactic medium (IGM) and re-ionize the Universe. UV imaging in several UV bands from 912-2400 Angstroms with ~arcsec resolution will be used to study the ~10 known local analog galaxies, and to assess the escape fraction of UV light and the characteristics of the galaxies that correlate with this parameter. A small fleet of micro-satellites would survey the local universe ($z<0.1$) for additional analog galaxies using several UV bands (either one band per satellite, or a filter wheel on each) to increase the statistical sample. UV detectors, optics and filters need to be studied, and there could be smaller CubeSat based demonstration missions prior to the full-scale mission.



Heliophysics Concepts

4.3 Heliophysics

The overarching goal of NASA's Heliophysics Division is to understand the Sun and its interactions with Earth, the solar system and the interstellar medium beyond. Three heliophysics mission concepts were developed at the workshop. For all three, the science goals are achieved through the use of multiple small, inexpensive satellites such as CubeSats. The first, the Ionosphere Magnetosphere Coupling Constellation, makes use of about 60 small, identical satellites to provide global coverage of the coupling between the ionosphere and the magnetosphere. Such a mission would be cost prohibitive using traditional spacecraft. The second and third concepts use a loose constellation of multiple small spacecraft and a "fractionated" approach to implement, at a much lower cost, "flagship class" missions previously proposed using traditional spacecraft. Fractionation, as used here, means that the payload and instrumentation are divided among the members of the constellation and not all members need to communicate directly with Earth. The primary advantages of fractionation are that (1) failed components can be replaced without the cost of replacing the entire mission; (2) the mission can be expanded and/or upgraded by replacing existing constellation members; and (3) multiple small, simple spacecraft are cheaper to build, integrate and tested than one complex spacecraft with many instruments and conflicting requirements. Other advantages of a fractionated approach for these two concepts are discussed below. The first and the second concept, the L5 Fractionated Space Weather Sentinels, were defined in much more detail than the third, the Solar Polar Constellation.

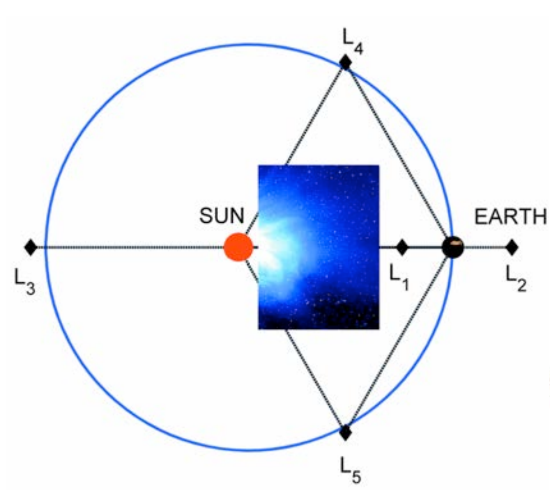
4.3.1 IMCC: Ionosphere Magnetosphere Coupling Constellation

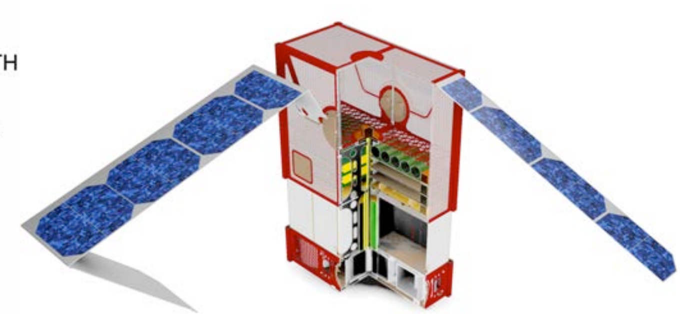
The most obvious effects of solar variability on the Earth's coupled ionosphere-magnetosphere system are geomagnetic storms, energized radiation belts, particle precipitation and aurora. The goal of the Ionosphere Magnetosphere Coupling Constellation is to determine how ionospheric circulation and energy dissipation are driven by, and feed back into, magnetospheric processes under a variety of solar wind conditions, from the inflow of quiet, steady solar wind to the dramatic impacts of large coronal mass ejections and their driven shock waves. There exist multiple pathways by which particles and electromagnetic energy flow between the ionosphere and the magnetosphere. The objective is to establish how field aligned electric currents, particle precipitation, electrical conductance, density and electric fields interact to determine the electrodynamic coupling of the ionosphere to magnetospheric drivers. Measurements with good spatial and temporal coverage of the entire ionosphere are needed to understand how the how the ionosphere is driven by, and participates in, the global circulation of plasma and energy throughout the coupled ionosphere-magnetosphere system.

These goals can be accomplished with a constellation of approximately 60 small identical satellites, each carrying three in situ instruments: a magnetometer, a plasma analyzer and an electric field antenna. The plasma analyzer will measure the flows of electrons and ions and their energy spectra. The magnetometer will give the local magnetic field and, in conjunction with measurements from neighboring constellation members, give the electric currents. The electric fields are measured with the electric antennas. Both the magnetometer and electric field antenna measure not only the DC fields, but also the oscillating wave fields up to about 100 Hz because waves also play an important role in heating the ionosphere and transporting energy. From these measurements, the electromagnetic energy (Poynting) flux and the electrical conductance can be derived. By measuring the Poynting and precipitation flux and comparing them with heating and upwelling, the flow of electromagnetic and thermal energy into and out of ionosphere can be tracked as function of geomagnetic activity and explain how ionosphere is driven by and participates in global circulation.

4.3.2 L5SWS: Fractionated L5 Space Weather Sentinels

The goal of this mission is to create an operational space weather base at the Earth-Sun L_5 Lagrange point, 60° east of the Sun-Earth line. L_5 is an ideal location for a space weather monitoring mission to provide early warning of Earth-directed solar storms (CMEs, shocks and associated solar energetic particles) so that the effects on power grids, spacecraft and communications systems can be mitigated. Such missions have been proposed using conventional spacecraft and chemical propulsion at costs of hundreds of millions of dollars. At the workshop, the participants developed a mission concept, a cluster of CubeSats, each ~6U in size, each carrying a portion of the science payload, that can accomplish many of the goals of a conventional single-spacecraft L5 mission, such as that described in the 2013 NRC Solar and Space Physics Decadal Survey / Report of the Panel on Solar and Heliospheric Physics.





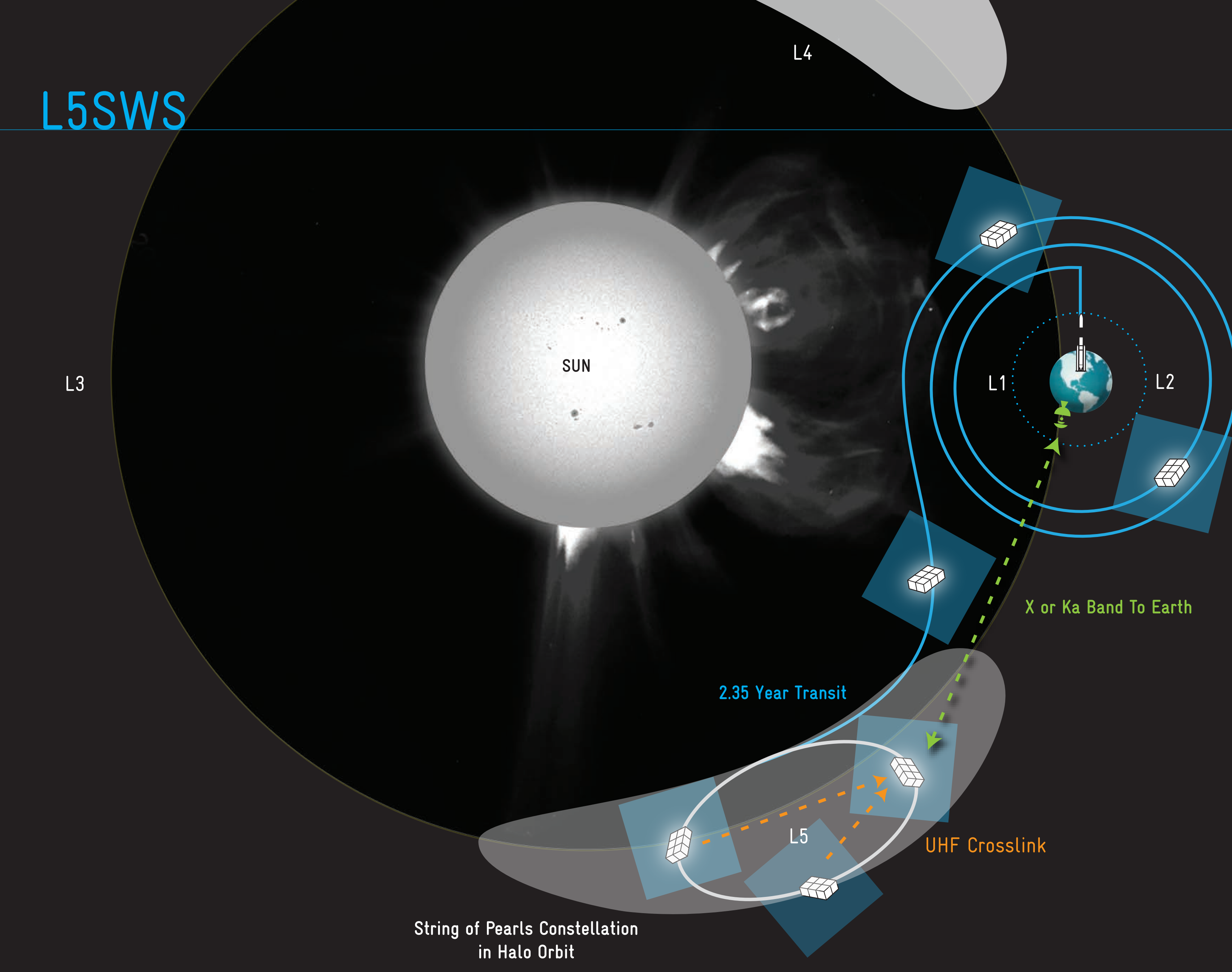
Key to L5 Space Weather Sentinels (SWS) is that only one of the CubeSats carries a high-gain antenna and other hardware necessary for communicating with Earth (~1 AU from L5). The other CubeSats, each carry one or two instruments, only communicate with the communication hub, which relays the data to Earth. The L5-SWS mission can later be expanded incrementally to add new instruments and new objectives by sending additional small spacecraft to the L_5 base. The mission described below represents a potential beginning for a permanent space warning system at L_5.

The ascendancy of CubeSats has brought renewed interest in solar sail propulsion because sail area scales directly with spacecraft mass. The concept presented here draws heavily on a NIAC study (Staehle et al, AIAA, 2012) that developed a 6U CubeSat architecture for interplanetary missions (A 6U CubeSat is 10 cm x 20 cm x 30 cm and is built from six 1U CubeSats, each 10 cm x 10 cm x10 cm). This study allocated 2U for a solar sail; the sail system was based on the Planetary Society's LightSail-1™ architecture (http://www.planetary.org/explore/projects/lightsail-solar-sailing/). In the SWS mission, each of the small ~6U interplanetary CubeSats reaches an orbit around L_5 using its own solar sail of approximately the LightSail-1™ size (~32 m^2), as in the NIAC study.

The SWS concept utilizes five ~6U interplanetary CubeSats: the first for communications to Earth, the second to carry the instruments to measure the interplanetary magnetic field and solar wind parameters (density, velocity and temperature), the third to carry the instruments necessary to characterize the solar energetic particles, the fourth to carry a white light telescope to image the coronal mass ejections (heliospheric imager), and the fifth to carry a magnetograph/dopplergraph to measure the magnetic fields and velocity fluctuations on the surface of the Sun.

While detailed engineering studies of this mission concept have not yet been done, there a several obvious advantages and cost savings to this approach. (1) Existing solar sails are sufficient for propulsion: A ~6U spacecraft with a sail approximately of the Lightsail-1™ size could reach an orbit around L5 in about 2 years. (2) Spacecraft requirements are eased when the fields and particles instruments are not on the same spacecraft as the imaging instruments: fields and particle instruments prefer spinning spacecraft whereas imaging spacecraft require 3-axis stabilization, and often instruments are susceptible to interference from each other. (3) Integration and testing, a major cost driver, is much easier and hence cheaper for several simpler small spacecraft than one large conventional spacecraft with many instruments. (4) The cluster can be built up incrementally. (5) If one CubeSat or its payload fails, only that spacecraft need be replaced. (6) Different agencies (e.g. NASA, ESA, NOAA, JAXA)

L5SWS

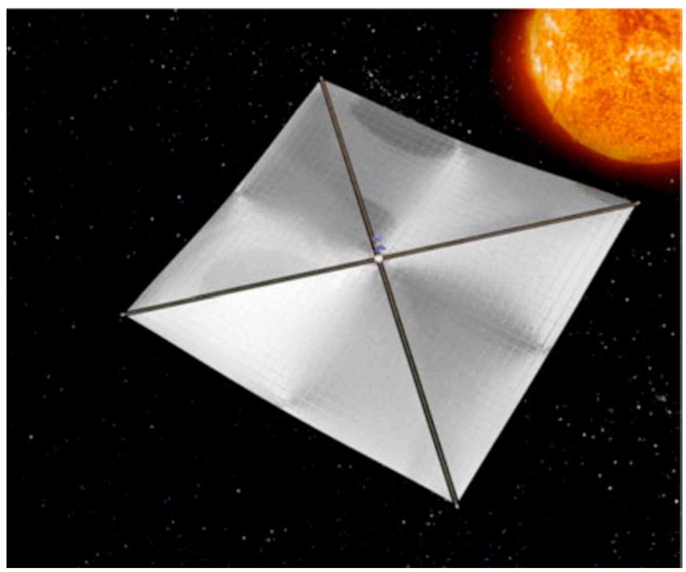


SPACECRAFT FORMATION	6 *CUBESATS*	• • • • • *STRING OF PEARLS*	**DEPLOYMENT TRAJECTORY**	*EARTH ESCAPE*	*HALO ORBIT*	**MISSION LIFETIME GOAL**	*CONTINUOUS*

could contribute their own CubeSat. (7) Individual CubeSats can be replaced to upgrade capabilities. (8) The Space Weather Base can be expanded later by adding other CubeSats with new instruments (solar coronagraph, solar EUV and X-ray imagers and spectrometers) to address additional science goals

The KISS study identified the major technological challenges for this concept. Solar sail trajectories to L_5 need to be optimized for this concept. Trade studies are needed to balance the desire for a tight cluster for intra-spacecraft communications against the orbit and navigation needs of each spacecraft. The instruments need to be miniaturized to fit into about 2U of the 6U interplanetary CubeSat; this is quite feasible for the instruments included in the five spacecraft SWS concept above, but more challenging for the imaging instruments of an expanded Space Weather Base, possibly requiring the use of somewhat larger spacecraft. More information about the concept can be found in Liewer et al. (2014).

4.3.3 SPC: Solar Polar Constellation



Our current understanding of the Sun and its atmosphere is severely limited by the lack of good observations of the polar regions. To address this requires a departure from the standard in-ecliptic set of observations to obtain a new perspective on the under-explored polar regions of the Sun. The Solar Polar Constellation uses a similar "fractionated" approach to that of the Space Weather Sentinels and uses solar sails to place a loose constellation of small spacecraft in a 0.48 AU circular orbit around the Sun with an inclination of 60-75°. This first direct view of the high latitude regions of the Sun would enable crucial observations not possible from the usual ecliptic viewpoint. Observations from such a vantage will revolutionize our understanding of the internal structure and dynamics of the Sun and its atmosphere. The rapid 4 month polar orbit combined with a suite of in situ and remote sensing instrumentation further enables unprecedented studies of the physical connection between the Sun, the solar wind, and solar energetic particles.

Such a mission using a single spacecraft and a solar sail has been studied extensively in the past as Solar Polar Imager (Liewer et al., 2009) and, under the name POLARIS, proposed as an ESA Cosmic Vision (Appourchaux et al., 2009). The payload includes both in situ (magnetometer, plasma and energetic particle analyzers) and remote sensing (coronagraph, magnetograph/Dopplergraph, EUV imager and spectrometer, Total Solar Irradiance Monitor) instruments. As in the SWS, the instruments would be spread among the constellation members and one spacecraft would be dedicated to relaying all the science data to Earth. This approach has all of the advantages from fractionation discussed in the previous section on the SWS mission. In addition, adding additional small spacecraft to give more complete coverage of the Sun more easily enhances the science return.

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Planetary Concepts Including NEOs and Small Bodies

4.4 Planetary

Planetary exploration is organized around three main science themes (NRC 2012) as well as measurements supporting Human spaceflight. The science themes can be summarized as:

- Building New Worlds: i.e., understand the origin of planetary bodies, planet satellite systems, or the origin of volatiles and organics in the inner Solar system.
- Planetary Habitats: i.e., search for and explore potentially habitable objects (past or present) and sources of volatiles and organics.
- Workings of the Solar System: i.e., characterize and understand processes that have shaped solar system bodies.

Details on science objectives relevant to each of these themes are summarized below and in Castillo-Rogez et al. (2012).

Theme	Measurements	Requirements	Instruments	Tech Challenge
Origins	Isotopic, elemental, mineralogical composition	In situ, extreme environments	TLS, APXS, XRF, Raman, LIBS, MassSpec	Deployment and Landing
		Returned sample (small bodies)	Sample Return Capsule/Acquisition	Deployment Navigation
Planetary Habitats	Volatile, organics composition, endogenic activity, heat budget, environment	In situ	MassSpec and variants	Instrumentation (sample acquisition and processing)
Processes	Atmospheric structure, fields, plasma, dust	Close proximity, in situ, multiple data points	Mag, transponders, Langmuir probes	Telecom, attitude control
Human Exploration	Dust, fields, radiation, gravity field, orbital properties, Regolith mechanical properties, ISRU (composition)	Close proximity, in situ, extreme environments possibly as CubeSats	Dust counter, ND, Geophysics Inst., APXS, XRF, MAG, Transponders RAD, Surface perturbation	Telecom, Nav, goal-dependent

Measurements to support Human Space Flight are presented as Gap Filling Activities (GFAs) meant to resolve Strategic Knowledge Gaps (SKGs) (e.g., Wargo 2012). The goals of these measurements are to collect data that can inform the strategy for Human exploration in order to reduce risk for crew, and operational risk, maximize mission performance, increase science/engineering reliability and return, and reduce the overall cost of the Human mission. Relevant observations may inform risk associated with transit (e.g., radiations), proximity operations (e.g., risk associated with descent and landing), and in situ operations.

Several architectures could be considered for the planetary science NanoSat, each providing benefits and capability, but imposing requirements as well:

Primary Propulsion / Primary Spacecraft: Providing a NanoSat with basic propulsion (> 100m/s) is quickly becoming realizable as 10m solar sails (Klesh et al. 2012b) and electric propulsion (Marrese-Reading et al. 2010, Hruby et al. 2012) systems are miniaturized and reach the marketplace. These systems would allow a NanoSat to be delivered to Earth orbit (likely Geostationary Earth Orbit (GEO) or escape orbit), from where it could depart and head to the Moon, Sun-Earth Lagrange points, asteroids, or even Mars, within interesting (< 5 year) timelines (Klesh et al. 2012b, Hruby et al. 2012, Staehle et al. 2012, Strange et al. 2012). These systems would be self-contained, with direct-to-Earth communication systems, while being able to operate in clusters or constellations.

Mothership-Daughtership: The ability to deploy a NanoSat from a larger mothership would provide quite a few advantages to the NanoSat: The smaller vehicle could remain shielded during the cruise to the target of interest; the mothership could provide a communication relay, reducing power requirements on the NanoSat; the mothership could provide charging during cruise; the mothership could pull high-powered processing on-board from the NanoSat; and the mothership could provide navigation assistance. But the NanoSat would also provide benefits: a relative-navigation beacon; a low-cost observer from a new vantage point; a disposable asset for proximity / dangerous investigations, for localization, etc. Some of these arrangements would depend upon the role of the NanoSat: (a) independent investigator (i.e., only required a ride to the target), (b) cooperative asset (i.e., NanoSat could fulfill secondary science objectives), or (c) collaborative (i.e., primary science objectives would not be met without the use of a NanoSat in conjunction with the mothership).

Formation / Constellation: With appropriate risk posture, NanoSats could remain at low cost even for large science missions. Large groups of NanoSats, flying in proximity to each other, could provide sparse arrays or distributed sensing of a single target, such as the observation of the structure of Earth's magnetotail.

Fractionated Space: Since NanoSats can be limited in power per spacecraft, but still have large science requirements for data, DARPA and others have considered fractionated space concepts, where a suite of instruments might fly on several NanoSats in a constellation, and a single NanoSat, in close proximity to the others, would not have an instrument and instead act as a communication relay back to Earth. This splitting of functionality would retain the usefulness and cost of a small platform while meeting requirements. This strategy would offer the additional benefit of allowing for future instruments to be added to the formation as desired (whether for an upgrade or to replace a broken asset).

CubeSat-derived NanoSats would hit significant challenges as they begin to work in deep space:

Survivability: Radiation tolerance on CubeSats has always been hit-or-miss. The general strategy has been to use commercial parts, and reset or re-launch as needed. In the protected environment of low-Earth orbit, this has generally worked well. But as science missions require certain lifetime guarantees, radiation tolerance has become more of an issue. Away from LEO (and aside from the radiation belts, Jupiter or other high-radiation areas), the total ionizing dose generally decreases while the high-energy particle flux increases.

Thus, shielding alone, while useful, will not preserve the spacecraft. With fewer launch options available for deep space regions, re-launch may not be as feasible (though carrying multiple NanoSats onboard would be another way to accept the failure of a few vehicles). Examination of providing radiation tolerance in certain components, understanding when reset is acceptable, and investigating annealing processes would be required as NanoSats depart from Earth.

Communications: Transferring data and commands to and from Earth becomes much more difficult as the range to the spacecraft increases. Power, pointing accuracy, modulation schemes and data rates could all affect how this data is transferred. As the Voyager spacecraft has shown, incredible distances can be overcome through creative solutions. However, existing small radios have typically been raising data throughput, not investigating a reduction in signal-to-noise to receive data at farther distances. In addition, ground resources to receive the data have not yet been identified for the typical low-operation-cost market of NanoSats. If instead the vehicle is to use a mothership as a relay, communications equipment would need to be developed for spacecraft-to-spacecraft communications, possibly through an Electra radio, which has become a useful asset at Mars.

Navigation: Without GPS (Global Positioning System), two-line-elements, Earth-horizon sensors, or other useful assets around the Earth, the position determination and navigation of deep-space NanoSats would be a significant challenge. Star trackers are becoming available in a small platform, but often have a difficult time seeing planets or asteroids. Clocks are generally poor (lower accuracy) compared to the ultra-stable oscillator used by larger spacecraft leading to poor radio tracking. LMRST-Sat (Duncan et al. 2010) promises to provide a two-way navigation solution that would interact with ground assets to provide position information, but few other options are yet available. However it is also worth investigating the actual navigational requirements - many large missions might require meter-scale accuracy, but a great deal of science might still be accomplished at greater than 1-kilometer accuracy - this could significantly reduce the navigational challenge.

Attitude Control: Without a magnetic field to "push" on, attitude control becomes more challenging. Reaction wheels would still need a method for desaturating, while the constrained volume of a NanoSat does not allow for the typical cold-gas solution to last very long (which may be acceptable for potentially short missions). Here, the low inertia of a NanoSat would make solar-radiation-pressure a possible acceptable alternative for reaction wheel desaturation. Other schemes, such as using small EP (electric propulsion) thrusters, may also prove useful.

Propulsion: If the previous challenges are all met, then independent propulsion of a NanoSat may be achievable. However, giving a low-cost asset propulsion is also problematic to a mothership – should a problem arise the propulsive NanoSat could impact the mothership and induce significant risk. Risk tolerance and acceptability is a challenge that must be examined for any NanoSat, but it is of particular importance when propulsion is added. As solar sails, electric propulsion, and chemical systems become small enough for that type of platform, examination of risk acceptance must be reconsidered – indeed, the first CubeSats were not allowed to have propulsive elements when departing from a launch vehicle due to a concern regarding pressurized or energy storage systems that were considered an additional hazard rather than a risk of re-impact.

It is interesting to note that only the first three challenges require demonstration in deep space to fully test the system readiness. Attitude control without use of a magnetic field could still be demonstrated in LEO, and solar-radiation-pressure attitude control could be tested in GEO. Cold-gas and EP systems are already being planned for LEO, and solar sails could also be tested in GEO. For a full systems test, Survivability, Communications, and Navigation should be tested in a deep space environment.

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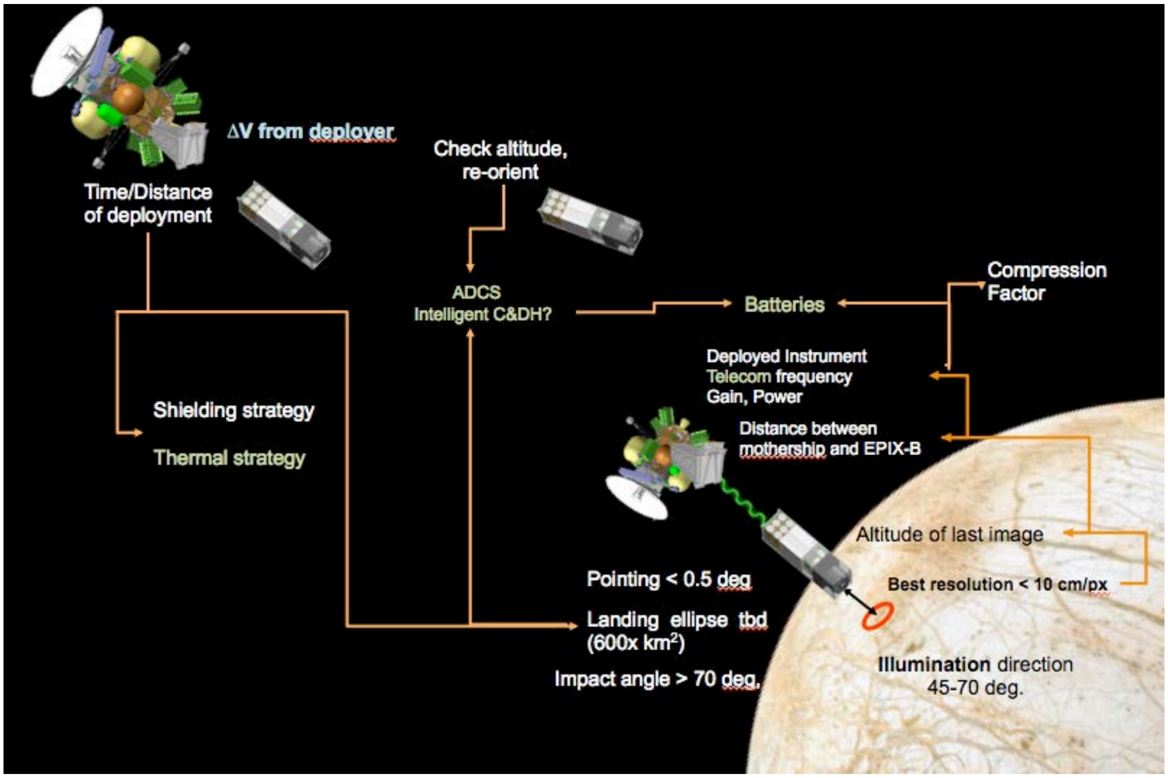
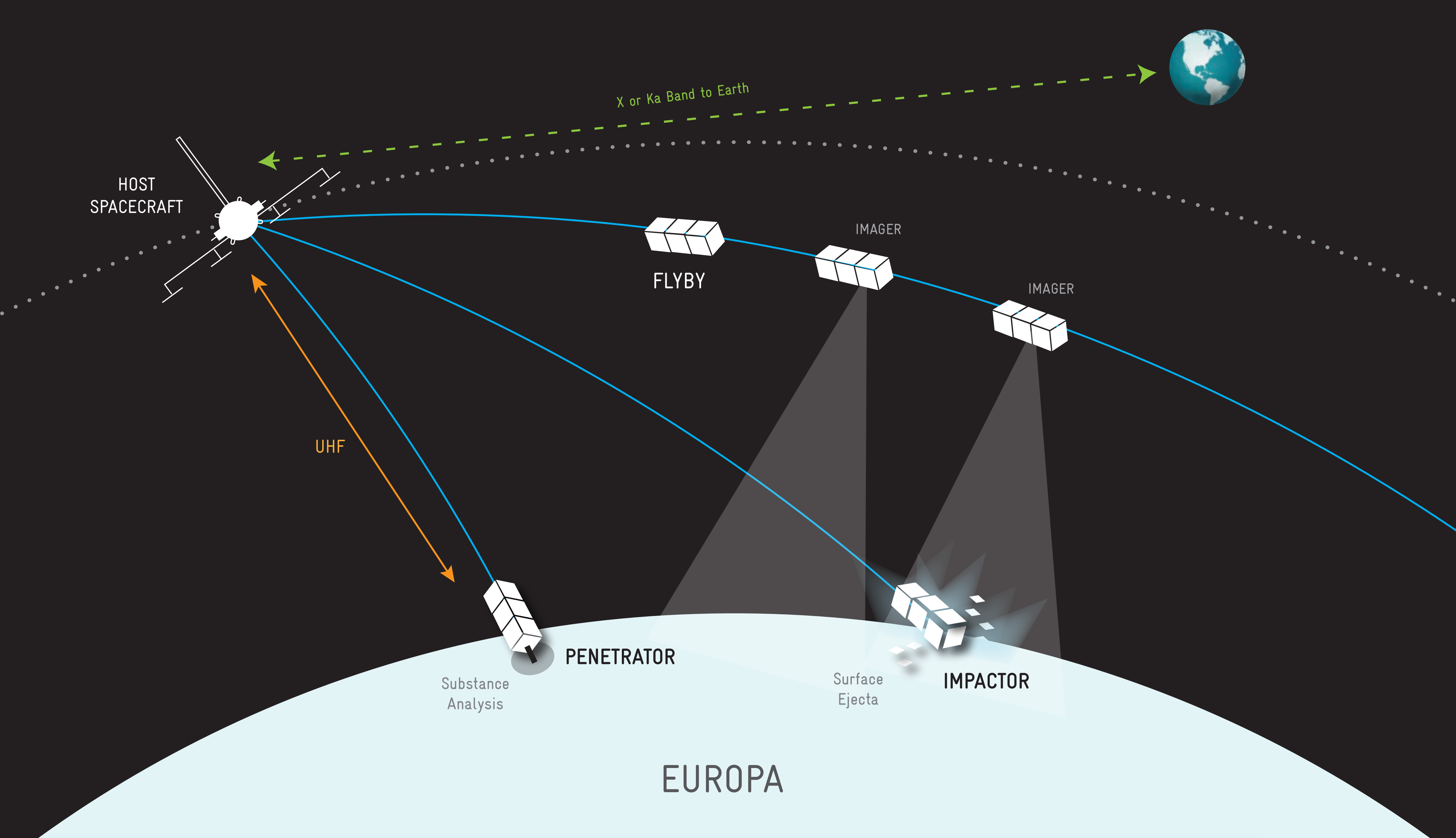


Concept of operations and key parameters driving the design. Limited aperture and photon counting, sets a max altitude for last image, which in turn sets telecom requirement for trajectory framework.

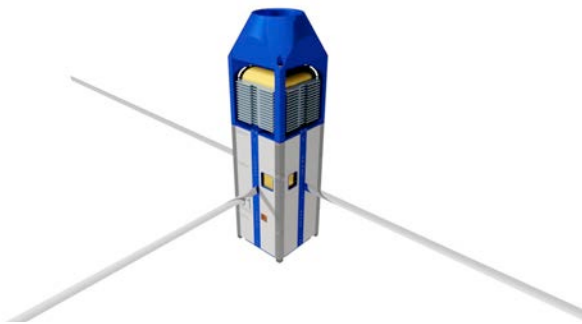
4.4.1 ExCSITE: Europa Fly-By and Penetrator

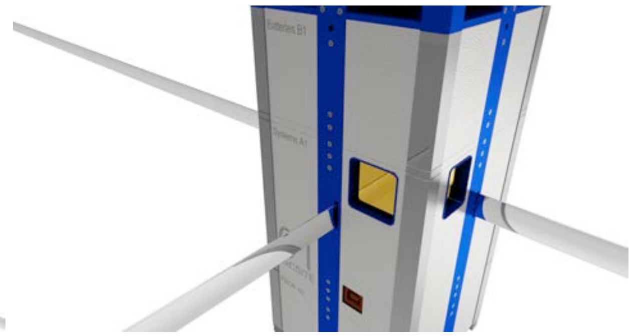
The Explorer Cubesat for Student Involvement in Travels to Europa (ExCSITE) is meant as a smart instrument to be deployed from the Europa Clipper mission as it flies by Jupiter's ocean-moon Europa. Depending on the launch vehicle available to the Clipper mission, the mothership may have enough mass margin to carry a dozen of small- and nanosatellites (Europa Project Study Report 2012). The ExCSITE platform would provide a pathfinder for university exploration of deep space through the deployment of science instruments accomplishing key objectives highlighted in the science traceability matrix for Clipper. These include high-resolution imaging of the surface with the Cubesat getting very close to Europa's surface; particle and field (magnetic/gravity) mapping through the deployment of several assets that would sample multiple regions of Europa's induced field and track its temporal variations as a means to constrain the properties (salinity, geometry) of the deep ocean; chemistry characterization of dust ejecta from Europa with a dust spectrometer performing a shallow flyby in very close proximity (<5 km) to Europa's surface.

ExCSITE



SPACECRAFT FORMATION	12 CUBESATS	FLYBY	DEPLOYMENT TRAJECTORY	HOST DEPLOYMENT	JOVIAN ENVIRONMENT	MISSION LIFETIME GOAL	3 YEARS





Small instruments could be transported to low altitudes by a Cubesat derived platform providing shielding, batteries, and on-board autonomy. Several deployable instruments on Cubesat platforms could be carried by the Clipper mothership, contained within deployers providing further shielding and telecom relay. Hence, deployed experiments could be performed independently with minimal impact to other science planned for Clipper, and with little dependence on mothership resources except for power and data forwarding.

The following non-optimized proof-of-concept can be used to illustrate what is possible for a Europa Clipper daughter nanosat, taking a deployed imager as reference case. The goals of this experiment are (a) to provide an image (panchromatic) of a 5 x 50 m rectangle on Europa's surface at 10cm resolution (5 cm/pixel captured with 100% margin), (b) to capture and relay context images on the way in sufficient to accurately locate the final image location relative to features observed by other instruments on Clipper. A representative scenario calls for an impact with Europa at 70° off surface (20° off vertical) angle while the sun angle is at 45° (good tradeoff between illumination and shadow length) and pointing accuracy of 0.5°.

1- Deployment: If necessary, Clipper changes attitude temporarily to deploy imaging instrument (see configuration in Table 4) orthogonal to the Clipper trajectory at 4 m/s (imparted by the deployer) when 4 days away from closest approach.

2- Using the camera and ADCS, eliminate tipoff rotations and determine 3-axis pointing to find Europa using the imager. Use the deployed instrument's radio and the Clipper-deployer radio in loopback mode to establish actual ejection speed using Doppler measurement. Using Clipper's navigation knowledge as a baseline and assuming knowable ejection speed and direction, calculate rough trajectory and impact time.

3- Deployment + 1 hr, impact countdown timer is set based on step 2. All power is turned off except the timer and wake-up circuit while electrical heaters maintain equipment at minimum operating temperature for wake-up.

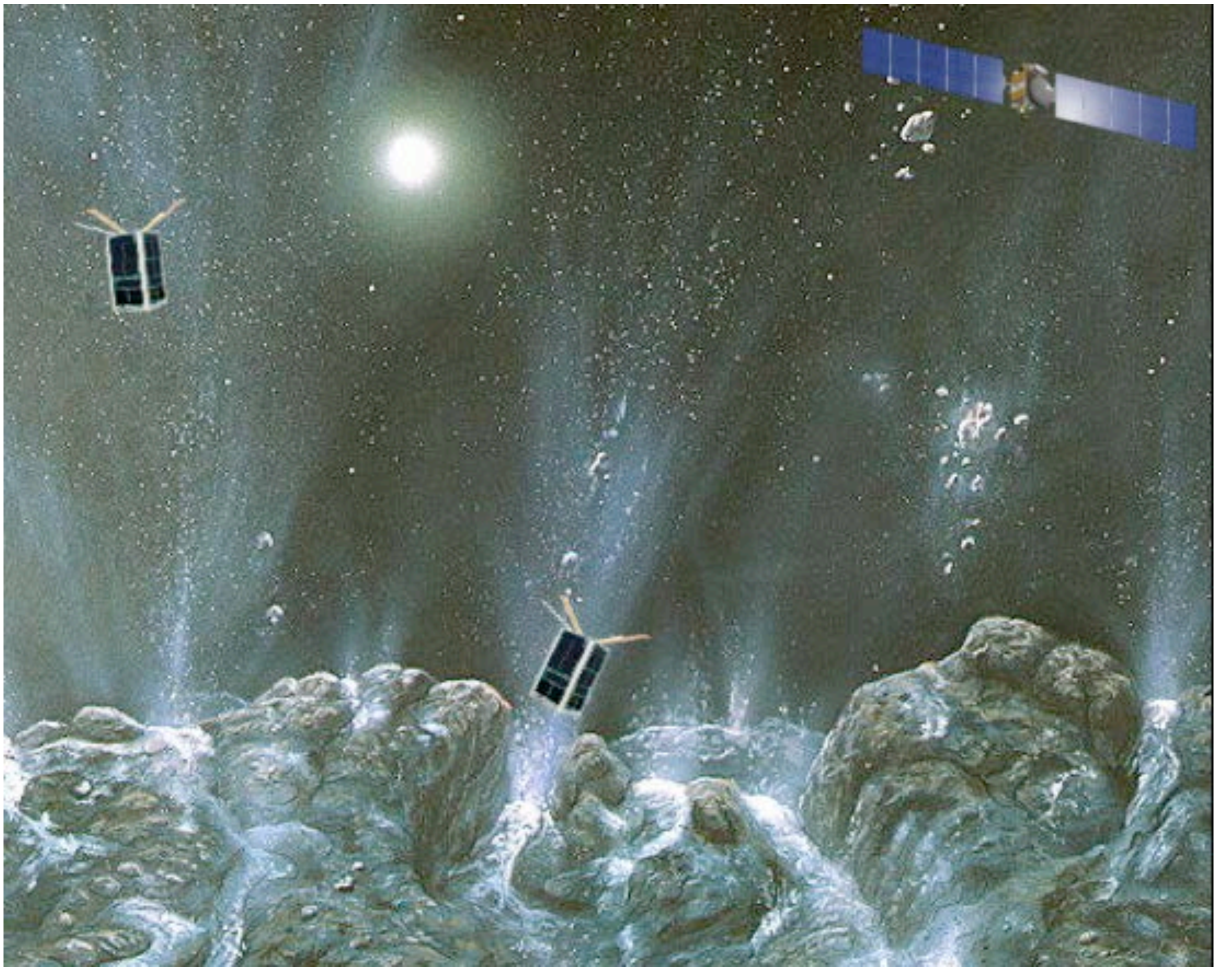
4- Turn-on feature detection when 1 hour away and altitude ~16,920 km. Use closed loop analysis of successive images for perspective change and radial image blur to maintain calculate desired centerline pointing within 0.5° or better of impact point.

5- 100x1000 pixel images will be streamed back to the Clipper at 8 frames/sec for the last hour.

Key technical challenges include: shielding strategies (systems and subsystems) for survivability in high radiation environment; novel techniques for handling stringent planetary protection requirements; fine-grained power management techniques; deployer with integrated communication, command and data handling independent from the mothership's systems (to minimize risk); increased deployment control for trajectory optimization; low-power telecom systems to enable extended communication windows between the mothership and its daughterships (i.e., 100,000s km, instead of a few 1000s km currently possible); miniaturized instrumentation.

4.4.2 C/entinel: Small Body In-Situ Exploration

The investigation of small-body objects, including asteroids and comets, offers multiple attractive mission opportunities, with benefits in the scientific, exploration and defense realms. For mission safety, and conservation of resources, most missions so far have limited their closest approach of small bodies to several tens of kilometers – with the notable exceptions of the orbiter-turned-landers NEAR and Hayabusa. The NEO-probe architecture introduces a new paradigm to reduce cost and risk taking advantage of nano-spacecraft (e.g., CubeSat) as a low-cost platform for close-in and in situ exploration of small bodies. This platform would carry instrumentation to obtain measurement of key strategic knowledge gaps identified by the NRC study "Defending Planet Earth" (2010): internal structure, mass, size shape, geology (morphology, collisional history), elemental and mineralogical composition, rotational properties, near surface mechanical and thermal properties, and variations of these properties at all scales. Missions to perform these measurements would in turn contribute to a more general understanding of small body interiors and origin reservoirs that ties to key science themes ("Building Blocks", "Processes") emphasized in the Planetary Science Decadal Survey. Most importantly, close proximity and in situ observations would provide ground truth information to calibrate our understanding of remote observations (e.g., ground-based RADAR, space observatories).



Small body near surface and interior probing requires in situ exploration techniques. Disposable probes impacting and interacting with the surface offer an avenue for low-cost in situ exploration responsive to the priorities of the decadal survey and human exploration program.

Once the probe is separated from the mothership, challenging operations must occur, including descent and landing (hard or soft), communications, and basic survivability. Similar to the proposed Minerva 2 mission on Hayabusa 2, these small probes must deploy from the mothership, head to the surface (either controlled or uncontrolled), and survive. Simulations have provided promising results (Tardivel and Scheeres 2012) indicating that passive orbits are readily available to guarantee surface impact, and even limited targeting may be available. This class of probes is even amenable to surface mobility (Minerva, Hedgehog) once landed. Harder impacts might serve to disturb the body, or at least provide seismic events for remote characterization.

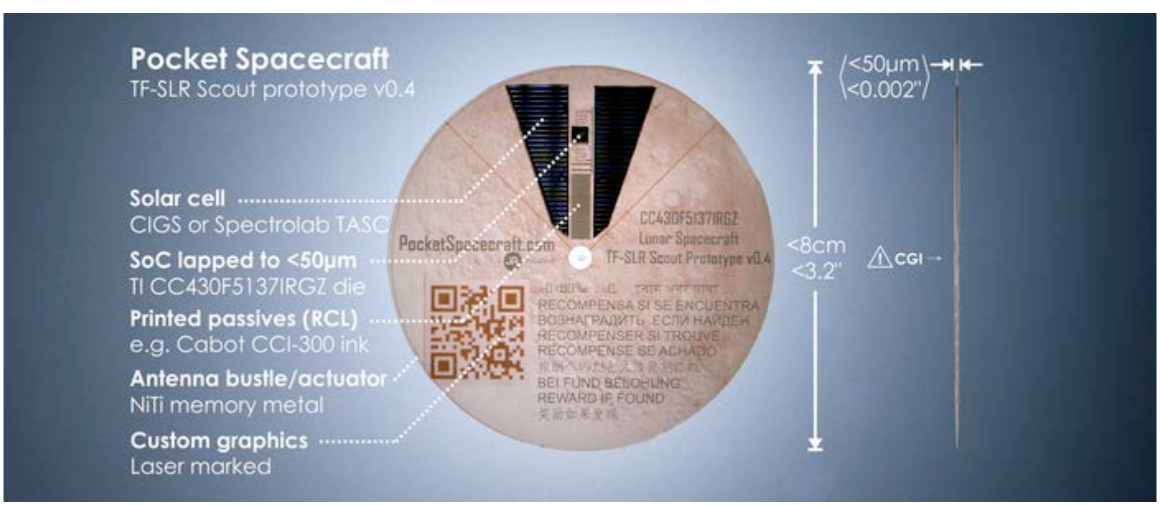
Results of the characterization of impact velocities upon small body objects show that low-mass craft can likely survive passive descent onto the surface of most objects (and even be targeted), yet more direct impacts for sub-surface exploration can also be utilized.

The proposed framework requires relatively cheap instruments and systems to be consistently deployed across multiple small-body objects. First, a carrier craft such as the Planetary Hitchhiker vehicle might be utilized to deploy probes and serve as a "cheap" communication relay. This architecture, however, requires the mothership to remain nearby for communications, an unlikely event if many objects are to be surveyed. Instead, probes with direct-to-Earth communication ability (even at extremely low data rates) may serve as a better long-term observation system to characterize spin, environmental evolution throughout an orbit (outgassing, mechanical stability, etc.), and affect of secondary objects. With a directional antenna, and a few Watt RF radio, low data rates can reach the Earth from even several AU distance.

It is quite possible that these sacrificial observation probes may also be useful for larger hazardous objects, where characterization by a mothership is impossible due to the risk of approach (potentially due to outgassing or other debris). Sacrificial probes provide a low-cost opportunity to reach inside the danger zone to characterize the surface, and provide insight into the appropriate methodology for defense.

4.4.3 Lunar Cube Vibrations: Lunar Seismology

The science driver for the Lunar Cube Vibrations mission concept is mapping and characterization of the interior structure of the moon and the search for volatiles and organics. These objectives are directly aligned with the interests of the Lunar Exploration Analysis Group (LEAG) and the Planetary Science Decadal Survey. The latter includes a lunar geophysical network as part of its New Frontiers mission concept portfolio.



(Courtesy JA / PocketSpacecraft.com)

Multiple low cost CubeSats, augmented with ChipSat / Thin-Film Spacecraft / Lander / Rover (TF-SLR) scale hard landing capable instruments with analytical and geotechnical sensors, would be widely and precisely distributed over the lunar surface. (TF-SLRs are postage-stamp to handkerchief-sized spacecraft at the gram to milligram-scale.)

Orbiting motherships, both dedicated and pre-existing would relay data to earth, with direct to earth telecommunications as an alternative data transport mechanism. When ridesharing to the moon, a single mothership would deploy all the surface packages. If solar sail or electric propulsion from geosynchronous transfer orbit (GTO) is used, multiple smaller motherships with a few sensors per mothership are preferred. A rideshare to low lunar orbit is expected to comprise approximately 50kg as seven 3U CubeSats on a system such as Mini-Surveyor or an ESPA ring.

Orbital insertion of the landers would be preceded by an optical reconnaissance period performed by the mothership or an existing orbiter. Deployment to one or more targets at apogee would be to an orbit that intersects the target. The mission would require a precision (within 1km) descent and landing at the CubeSat and/or ChipSat

scale, and would require survival of the instruments in a cryogenic environment in addition to the power and thermal cycling challenges. The descent and landing technique might be based on small thrusters, crushable structures or airbags and may build on the Lunette mission concept (Elliott and Alkalai 2009). The required survival time of the lander and instruments would vary from at least six hours for instruments looking for volatiles, to many weeks for seismometers. Instruments would continuously collect and store data, transmitting data of interest to motherships when they are in view. Advanced fine-grained power management solutions would increase lifetime and could enable long-term seismic monitoring.

Reference

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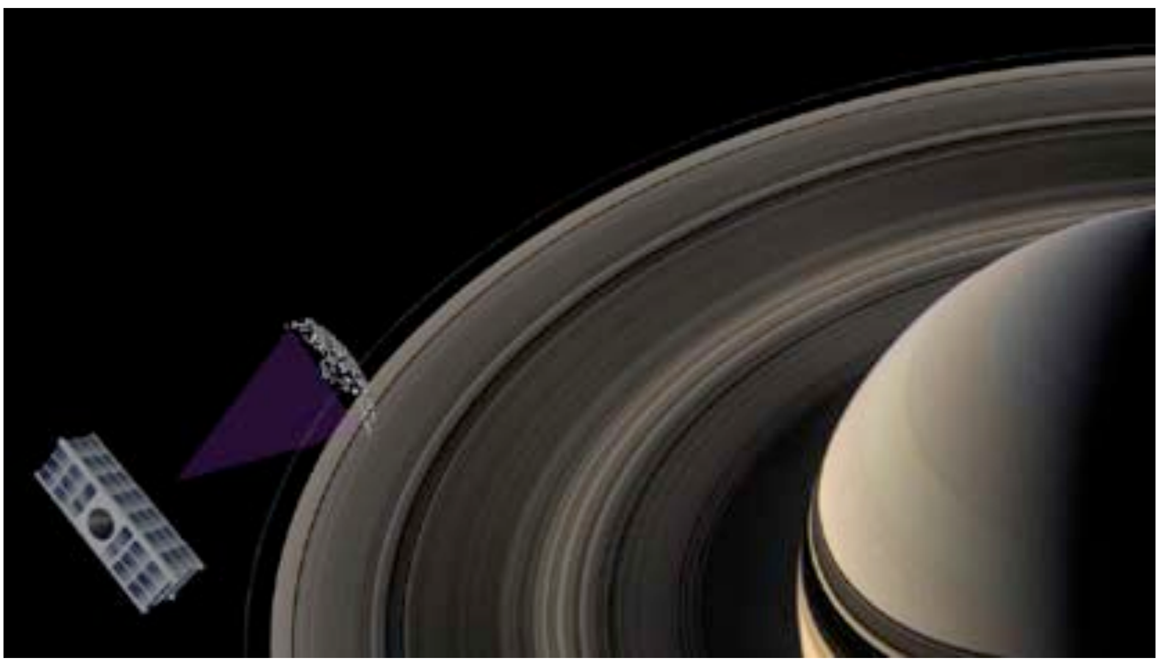


4.4.4 CHAMPAGNE: Planetary Ring Explorers

The composition and physical structure of Saturn's rings are not well understood. Science objectives of the CHAMPAGNE (CubeSat / ChipSat High Agility Multi Probe and Grid Network Explorer) mission concept include determining the spatial and velocity distributions, physical properties, size distribution of the ring particles and their location variations across the rings.

The mission would insert tens of thousands of ‘smart particles’ of a similar scale to ring particles into the rings permitting very close inspection and characterization. CubeSat/ESPA-scale motherships would enter orbit within 100,000 km of Saturn’s rings using their own on-board propulsion from Earth or piggybacking on another outer solar system mission. ChipSat / TF-SLR based smart particles, also possibly with on board propulsion, would be deployed into the rings in waves, with data from each smart particle wave downlinked and stored on in-range motherships.

Each smart particle would be tracked while in range of a mothership until destruction or until its maximum expected survival time is reached. Data would be locally processed and transmitted to Earth infrequently by the motherships via large thin film high gain antenna / solar arrays using high power burst transmissions limited by available energy harvesting and on board battery storage. Mission investigations would be complete within several weeks, but extended operations of motherships may last for years.

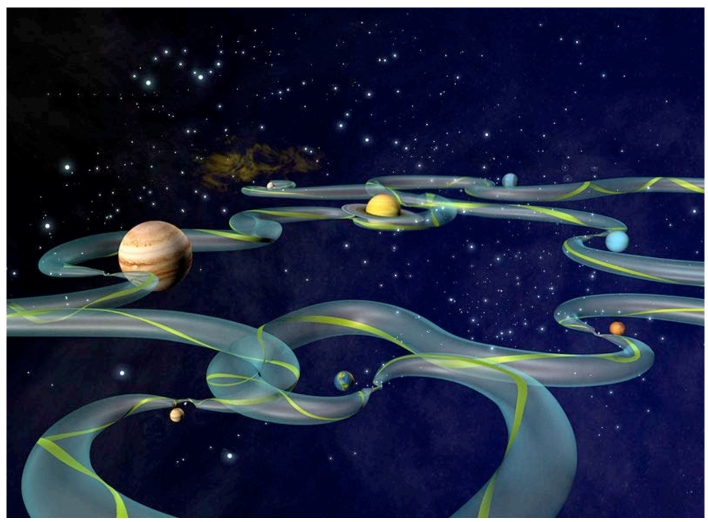
Simultaneous communication and position tracking of many (~100’s at a time) smart particles and multiple motherships would be required. A mixture of smart particle types including ‘drift through until destruction’, ‘ping pong balls’ and ‘sticky landers’ would be inserted into the rings to make different classes of measurement including their rate of attrition - a useful measurement in its own right. Multiple deployment events are preferred unless a one shot deployment during a flyby piggyback ride is necessary.

Technology issues include the development of small scale (3U to 24U) CubeSat motherships with propulsion and high gain thin film antenna / solar arrays, tracking and relay at up to 100,000 km for smart particle/mothership communications; the development of efficient infrequent ‘bursty’ communication systems (both ring probe to mothership and mothership to Earth); relay via other missions; on-board processing to cope with energy harvesting with storage type power systems to manage the power budget limitations of small motherships and smart particles at 9AU; Smart particle systems and instrumentation (accelerometers, transmitter, mm scale camera with fisheye lens, etc.) capable of surviving long cruise times will be required. Development of a heavily instrumented universal ChipSat / mass customizable TF-SLR with sufficient flexibility to allow the non-recurring engineering costs to be spread across a wide range of planetary science missions plus automated management systems for swarm missions will be important.

Technology Advancements and Future Challenges

5.1 Overview

Small satellites have flown technology validation and science experiments in LEO, but the effects and demands of the space environment for future missions beyond LEO require fundamental changes in spacecraft design. This is particularly true for small satellites, compared to traditional systems, as described in the planetary science section of this report. Principal among these challenges are the impacts of radiation effects, in-transit lifetime, navigation and control, communications, power, and the temperature/thermal environment. Furthermore, the new mission concepts described stretch the boundaries of technologies currently available to achieve them, but the goals of this study go beyond opening new areas of scientific investigation. The teams also addressed the challenges of new technologies that would be needed to enable the science.



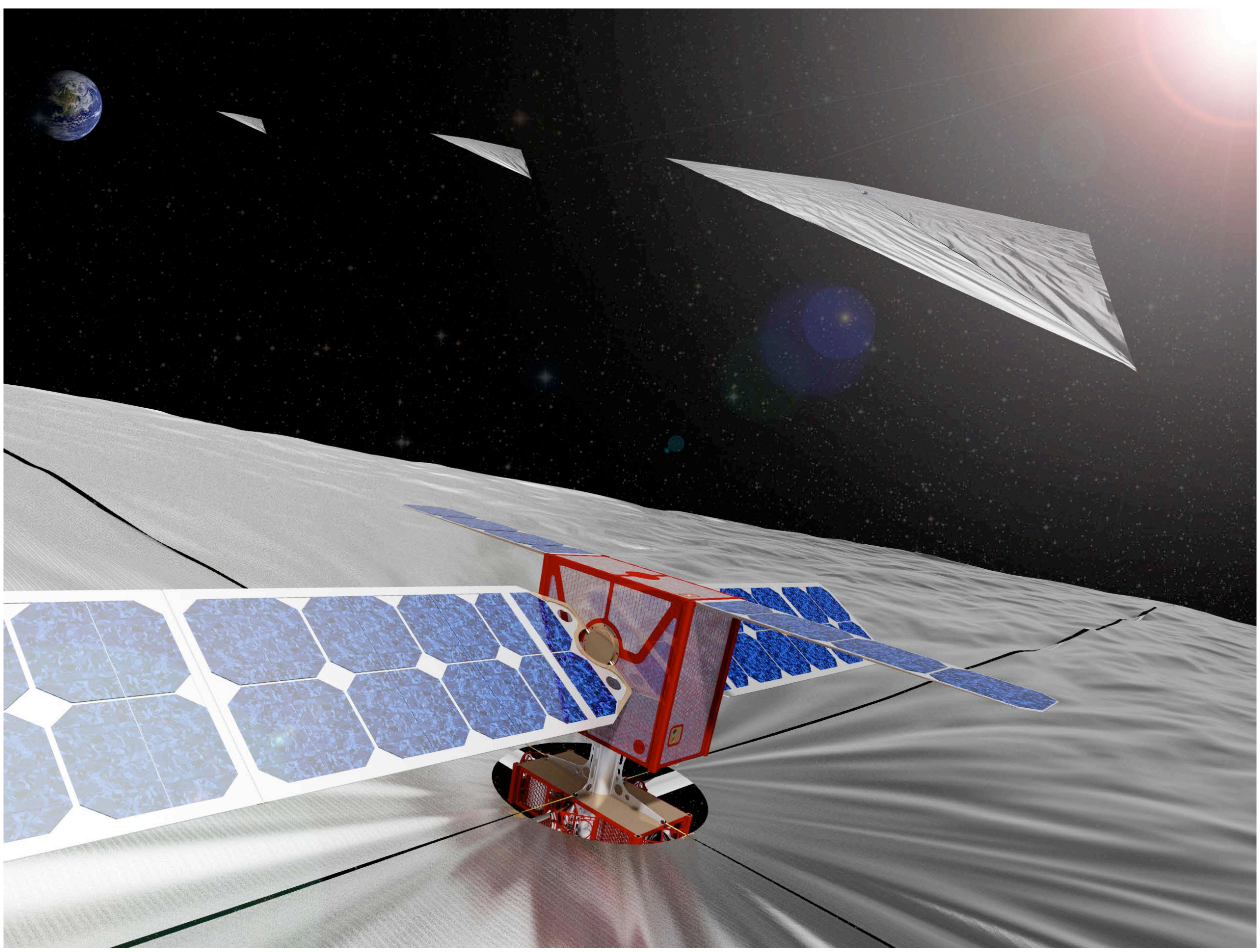
The first workshop explored new science investigations, but the emphasis of the second workshop and follow-on study period was to identify and explore the associated technology challenges needed to realize these kinds of concepts. Of course, deep space missions have been flown in the past and many of the challenges listed above have solutions for traditional missions. Nevertheless, considerations for small spacecraft, in some cases, challenge these approaches and there are special considerations and new technology approaches that must be revised or extended for these systems, such as in low-thrust trajectory and navigation design, and in some cases new technologies must be designed, such as in-space spacecraft manufacturing and refurbishment, among others.

A concurrent engineering study session was held to explore these issues for the L5SWS mission concept, and to serve as a pathfinder for additional spacecraft and mission design analysis work performed during the study period after the workshops. In this section details are given for three missions, one from each study area of heliophysics, astrophysics, and planetary science, where the engineering and technology challenges are explored and addressed. The proposed spacecraft designs are described and designed to engineering tolerances. Consideration is also given to existing components or new technologies that would need to be designed within the next five to twenty years – these designs are far more than “artist’s renderings”.

One might expect to see taxonomy of specific technologies, with performance metrics to advance, for small satellites beyond LEO exploration in this section. As this is an area moving very quickly, and in contemporary definition, the recording of such a list would not add value. In this section, we prefer to introduce the challenges and specific proposed solutions based on the study to meet the mission requirements emphasizing where new capabilities are needed while proposing forward-looking solutions to those challenges. In this way, the science is not impeded by existing, or future technologies, that might be developed or proposed and it intentionally leaves open the implementation techniques one might conceive to develop these kind of advanced mission concepts.

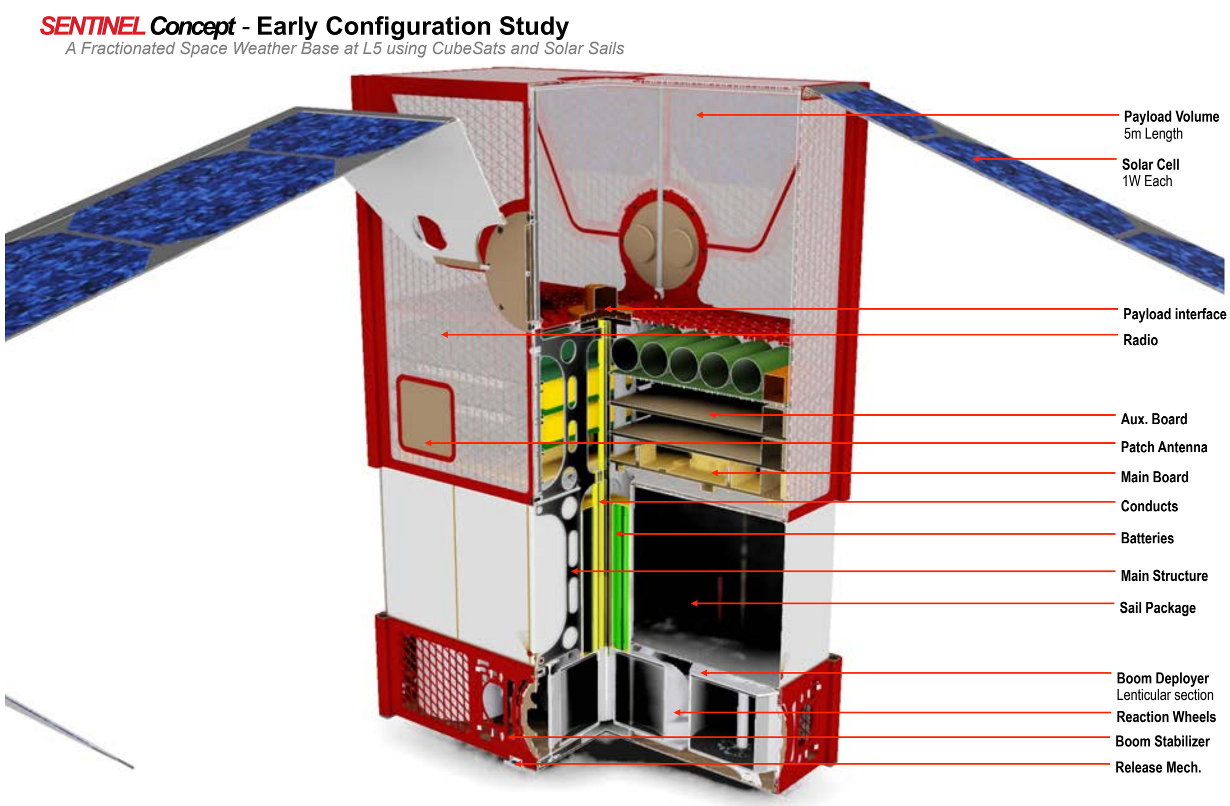
5.2 Concurrent Engineering: L5SWS In Detail

The L5 Space Weather Sentinels is a constellation mission concept that would be incrementally deployed to the Earth-Sun L5 point to continuously monitor effects



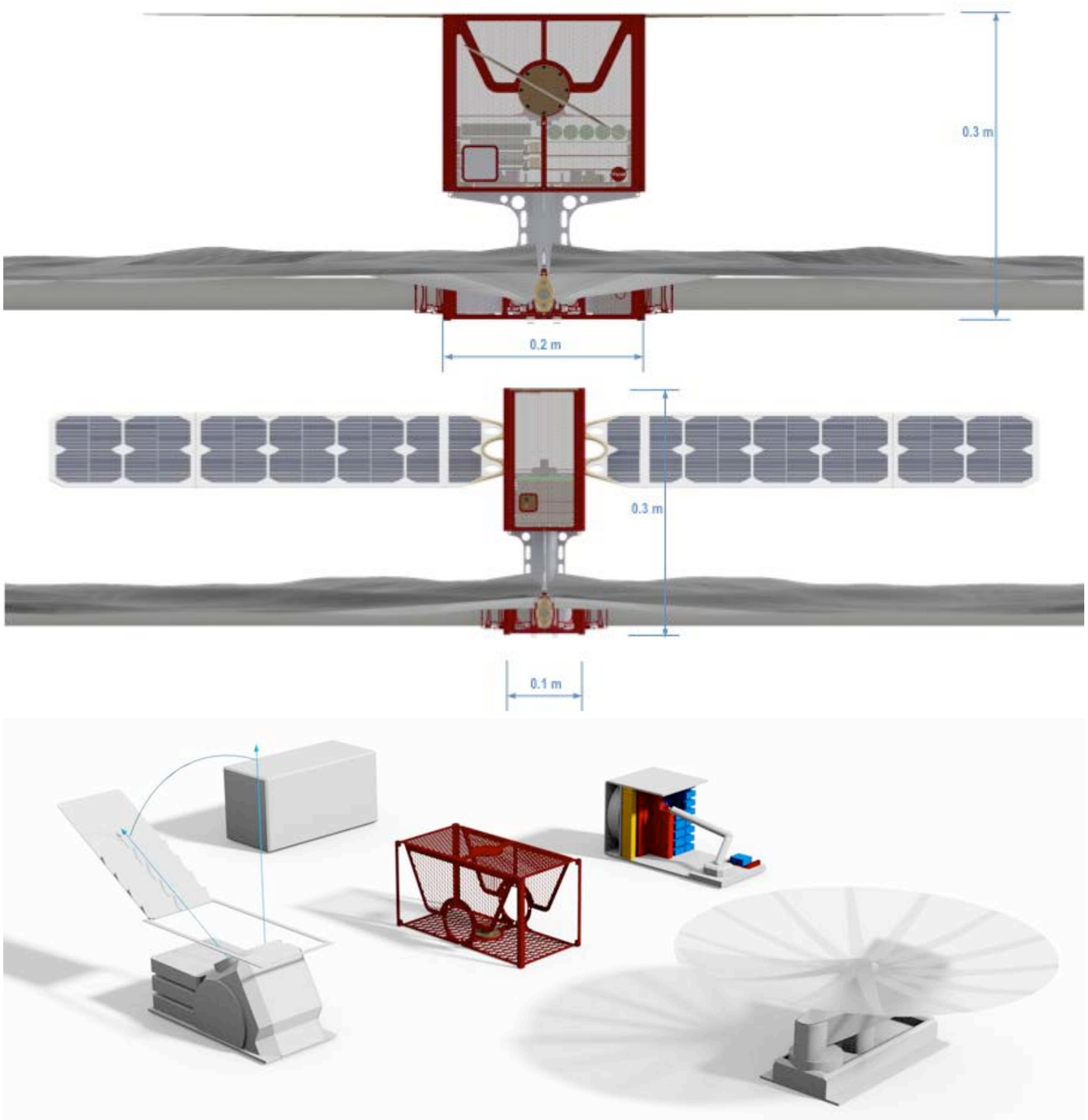
Conceptual Design of the L5 Space Weather Sentinels Mission Constellation Concept impacting the region from the solar surface to the Earth. In addition to a telecom spacecraft, each 6U CubeSat system would carry a specific instrument, such as a heliophysics imager, particle detectors, magnetometer, and so on. The 98 square meter solar sails are used for propulsion and deployed after the Earth escape trajectory providing both the low-energy trajectory mechanism to reach L5 and a means to stop and perform station keeping upon arrival at L5. This approach could achieve the desired spacecraft injection and observation attitude within 3 years from launch. Note that the wrinkles in the sail are calculated deformations under induced gravity effects and sail deployment.

The spacecraft bus design contains a number of new innovations that will be required of a mission of this kind. As broadly illustrated the sail packing and deployment mechanism is completely new. The booms design is based on a metallic glass amorphous metal (or potentially a composite) high tensile strength composite that can accommodate the deployment length of the sail while still fitting within a ½ U payload volume. The sail itself is composed of kapton that is especially lightweight to ensure that launch mass requirements can be maintained. Of particular note is the structure itself, which is made of a nanostructured polyaniline polymer that provides radiation

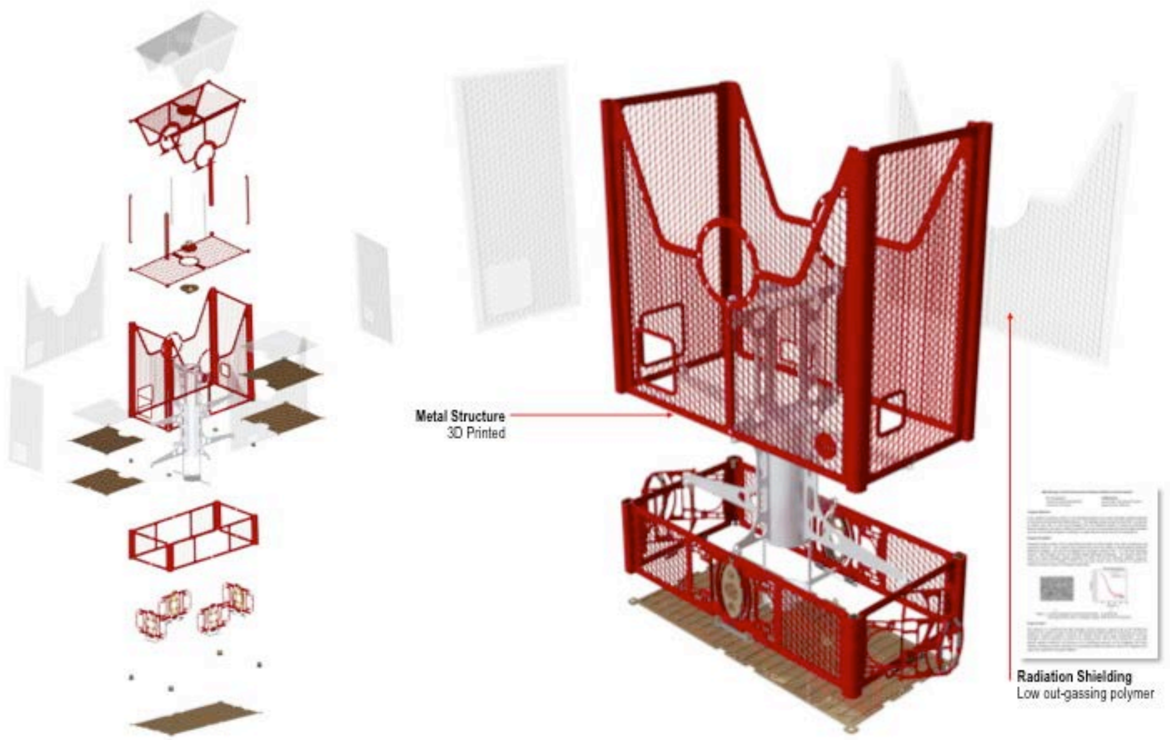


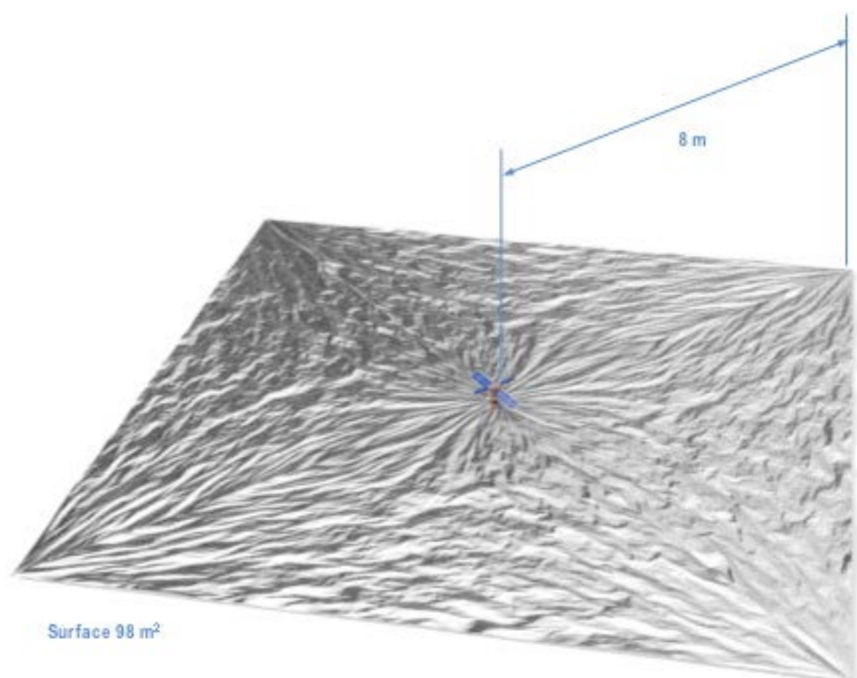
Details of the L5 Space Weather Sentinels 6U Bus shielding to the spacecraft bus and the associated payload.

The cut-away of the bus design highlights many, but not all, of the components of the system. The bus is not only a plug-and-play design, but also supports and is composed of additive manufacturing components enabling in-space component assembly from deployed 3D printing systems. Should servicing of the bus system, or the instrument accommodation, require a replacement the spacecraft system can receive and accommodate the necessary parts, and perform the in-space assembly, at L5 as needed. Although the mission design of the SWS mission supports full spacecraft replenishment and deployment to support the constellation mission, development of the in-space assembly feature enhances overall reliability of the system under unexpected potential failures.

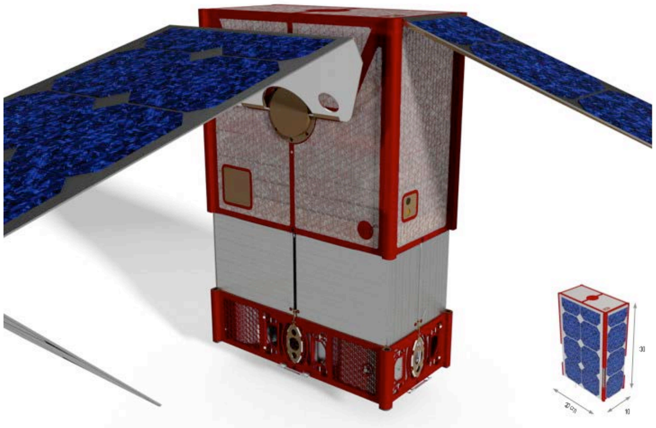
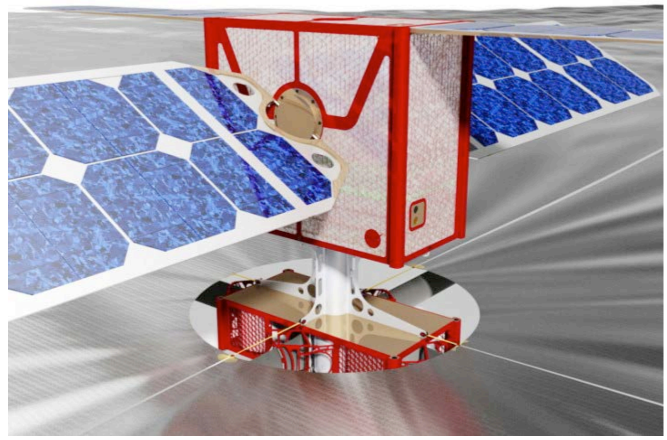


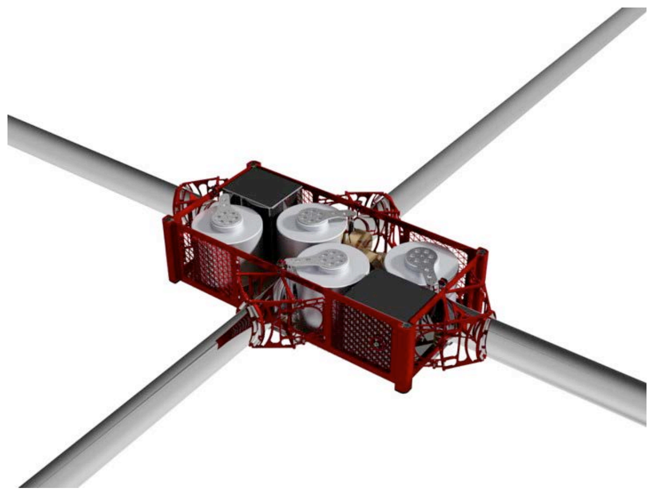
The engineering illustrations highlight additional design considerations of the spacecraft of including the deployment configuration and the in-space 3D printed assembly factory that can support in-space servicing of systems from L5 in instances where a replacement spacecraft need not be deployed. The “wrinkles” in the deployed sail are based on calculation of solar pressure effects given the sail dimensions.

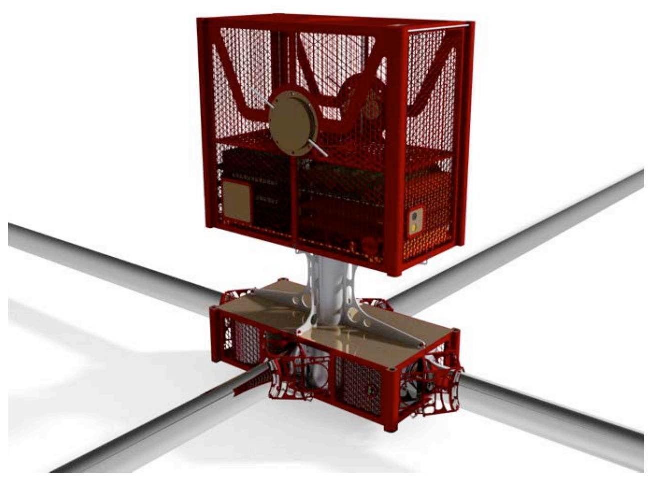




Finally, the deployment mechanism of the sail is illustrated in the close-up imagery below along with the full system in its stowed and deployed state. The internal support structure and radiation shield instrument payload section are viewable as well.

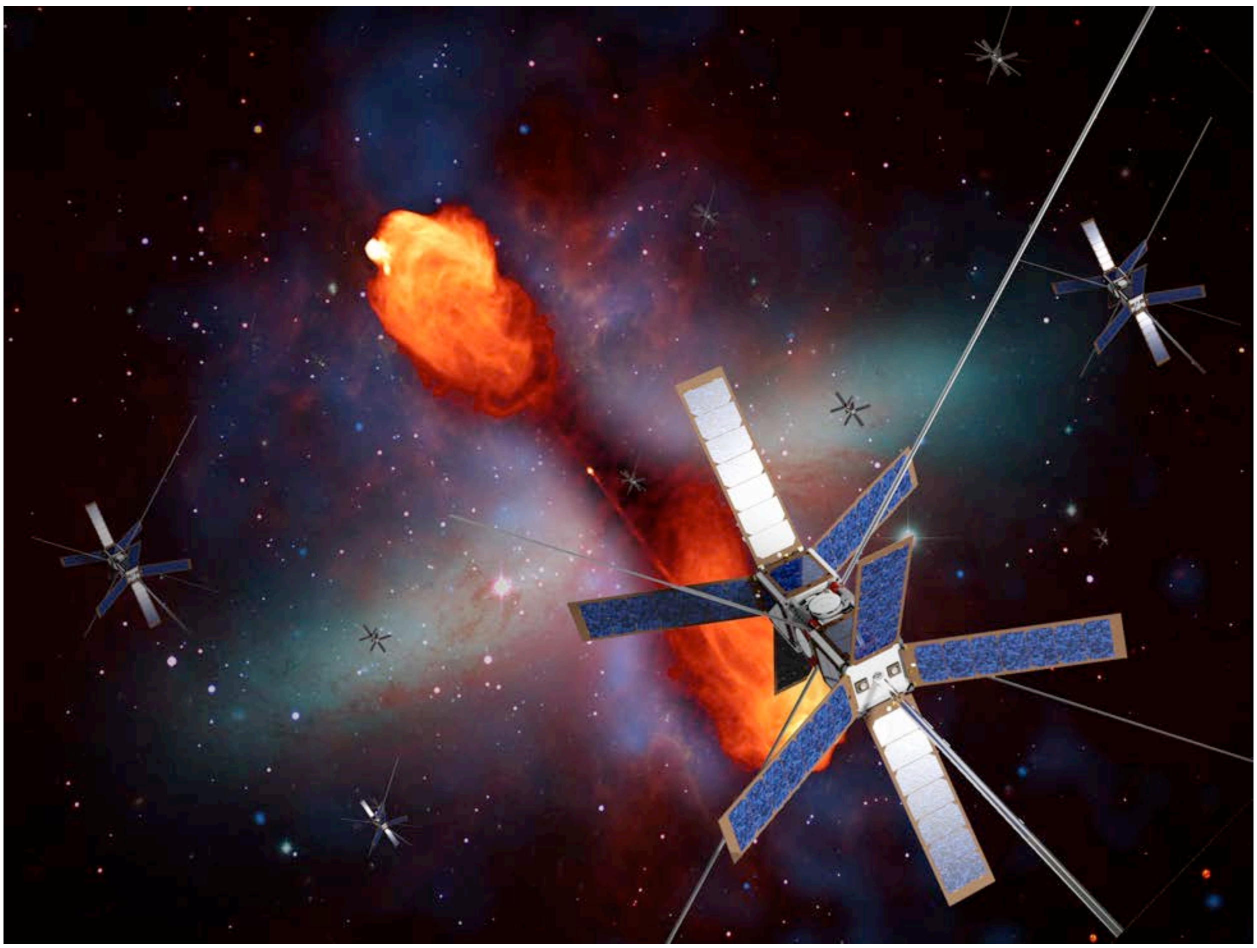







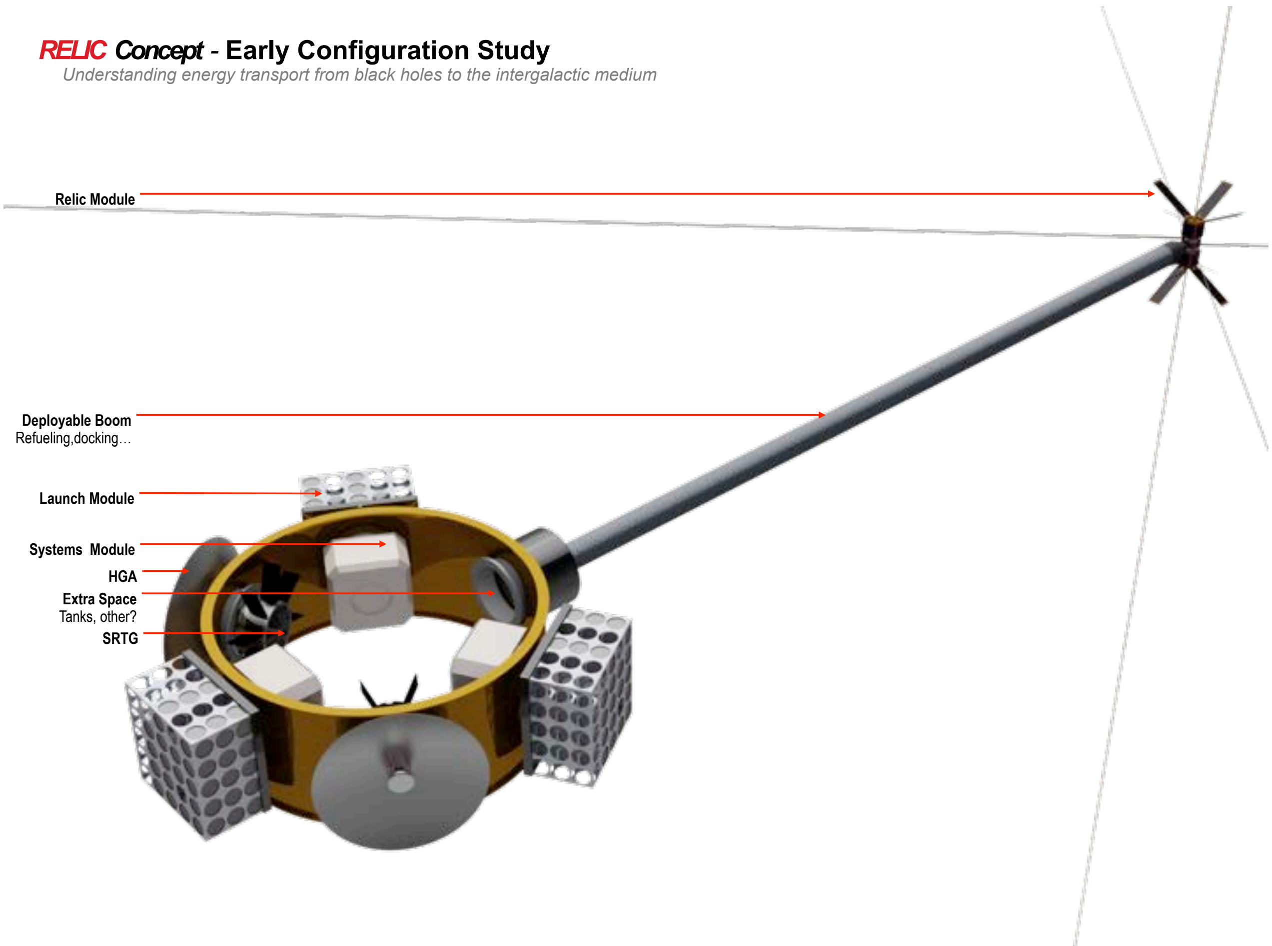
5.3 Concurrent Engineering: RELIC In Detail

The RELIC mission concept is a constellation designed to image double-lobed active galactic nuclei (DRAGNs) based on low-frequency observations to understand energy transport from black holes to the intergalactic medium. Aperture synthesis using a 1 km diameter spherical array of at least thirty 3U CubeSats deploying 5m-dipole antennas in each coordinate direction would establish imaging from the Earth-Sun L2 point, a drift-away orbit, or a lunar low-gravity gradient field environment. These basic requirements influenced the proposed systems engineering design that utilized a combination of existing and new technologies necessary to meet the unique scientific objectives of this mission concept.



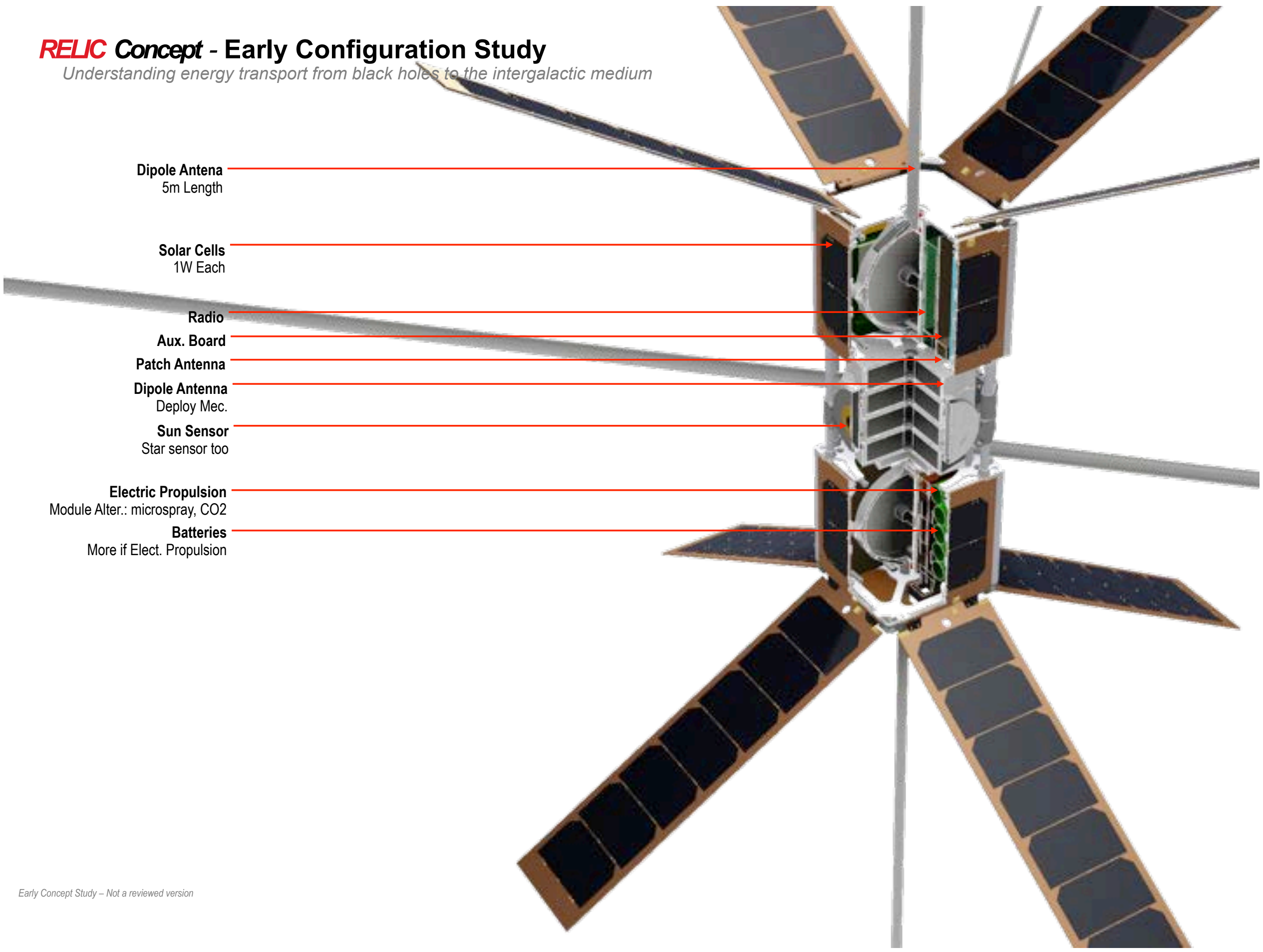
Conceptual Design of the RELIC Mission Constellation Concept

RELIC would be launched as a modified ESPA-ring spacecraft either as a secondary system with propulsive capability, or as a primary to a dedicated deployment attitude in a suitable radio quiet zone. In the design, the ESPA could carry three deployment modules each containing twenty 3U CubeSats for a total of sixty spacecraft where roughly thirty would be dedicated as receivers to the baseline mission while the remainder would be spares including compartments for replacement parts utilized for in-space servicing. The ESPA also carries two high gain antennas (HGAs) for Direct to Earth (DTE) communication of the radio observations. A retractable boom supports docking for in-space servicing, but not for deployment as the constellation would support autonomous assembly and deployment maintenance in the required spherical configuration. Stirling Radioisotope Thermoelectric Generators (SRTGs) would provide power for the host spacecraft functions as well as recharging capabilities for the observational spacecraft should that be required based on the deployment observation scenario.



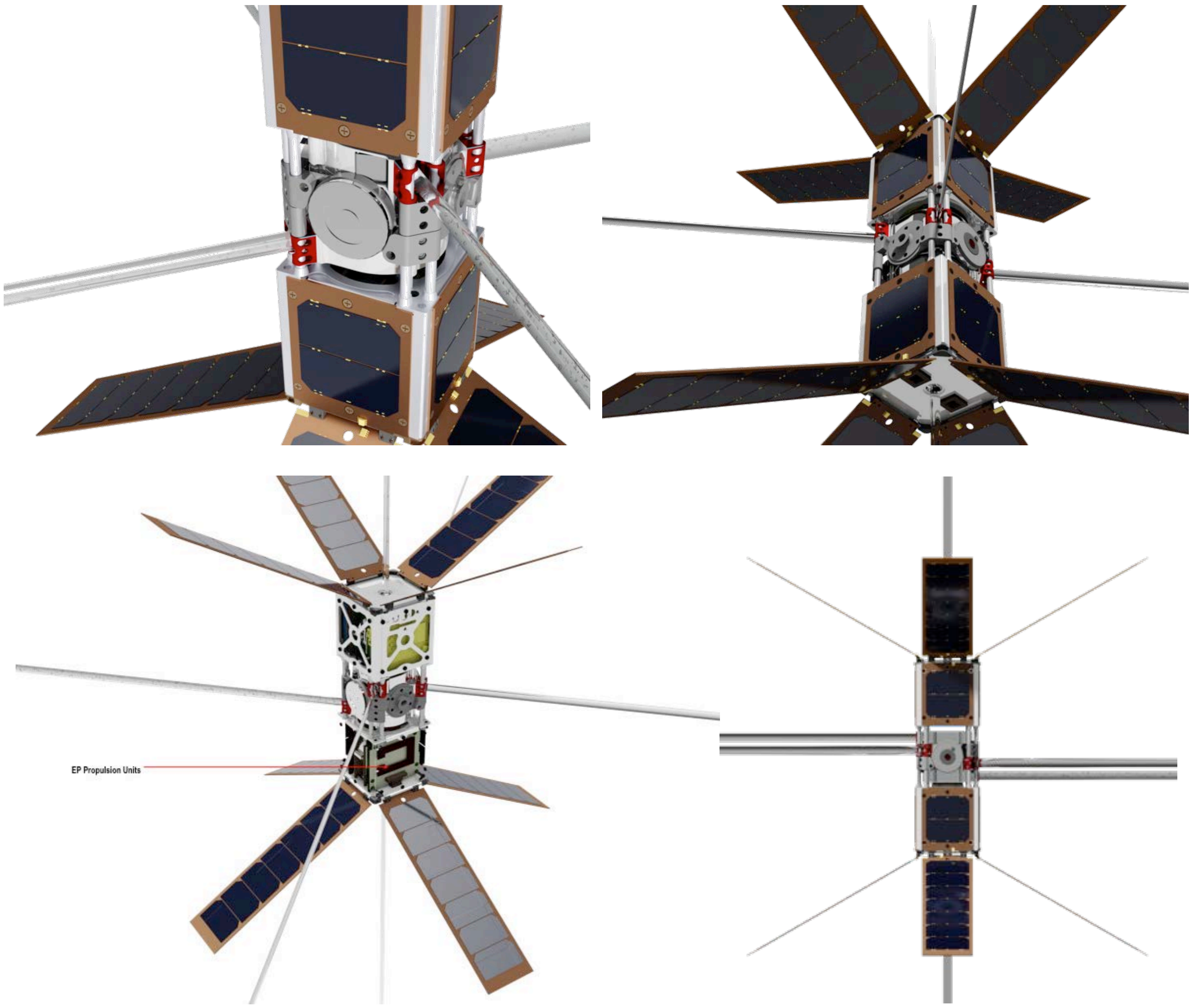
Details of the RELIC Host Spacecraft

While most of the innovations are in the constellation design there are a few key features of the measurement spacecraft to note as well. The 3U CubeSat, shown in the cut-away image, has been designed and rendered to specific engineering tolerances for form, fit and function. Of key interest are components such as the 5m-dipole antennas. The deployment design fits within a new housing integrated with the spacecraft to satisfy center of gravity (CG) requirements and controlled stored-energy deployment in the +/- x/y/z coordinate directions. The CubeSats support a combination of electric propulsion and cold gas for station keeping as well as for deployment from the host ESPA-class carrier and for any potential in-space servicing that may be required utilizing the host spacecraft. The radios and flight software enable autonomous constellation management as well as intra-satellite communication supporting the correlation calculations required of this measurement.



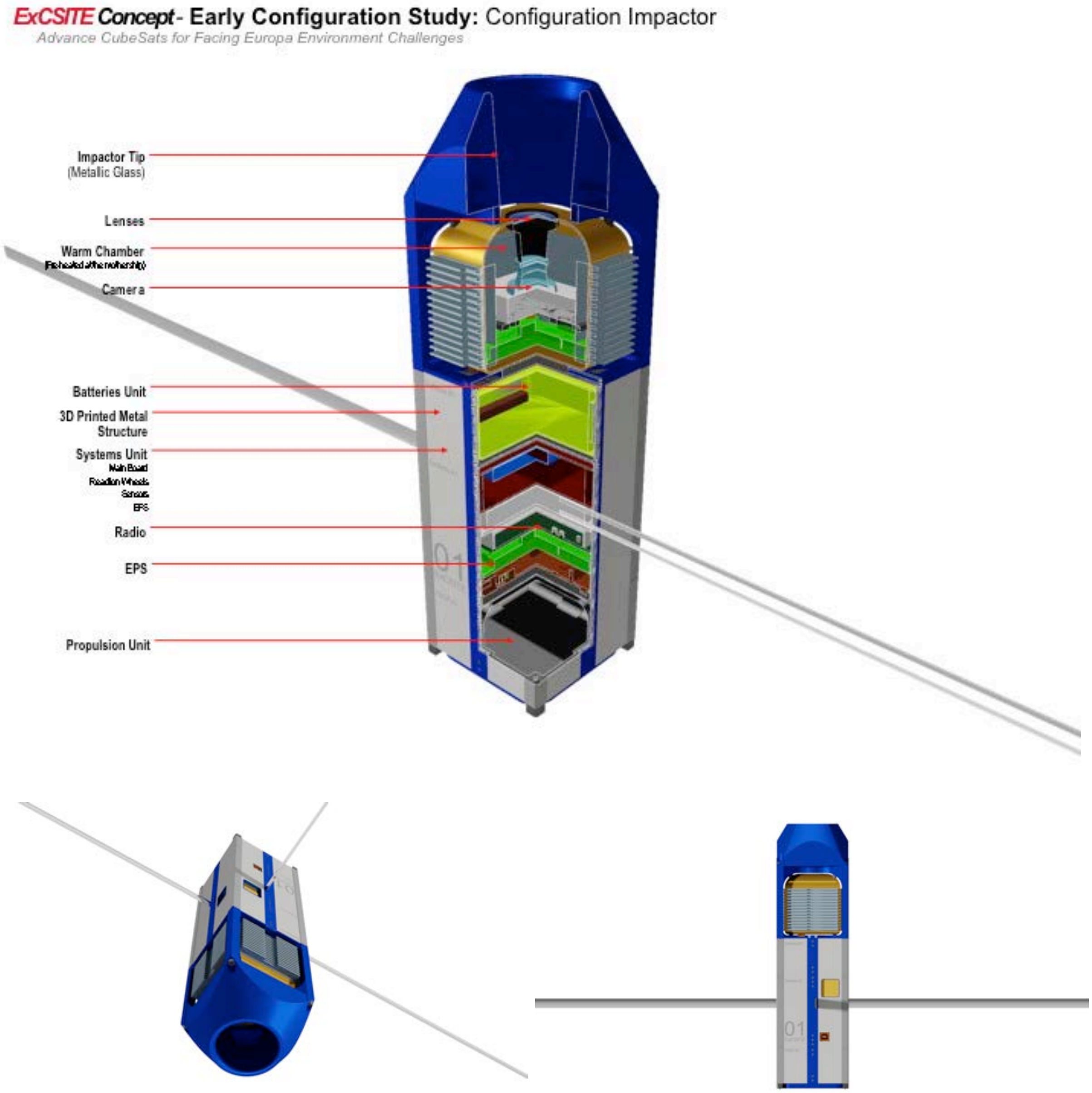
Details of the RELIC Measurement CubeSat

Some of the key technology advancements that would enable this mission include on-board and autonomous GNC software for precision formation flying to dynamically maintain the relative distances and structure of the CubeSat formation. Advances in radiation hardened electronics for high performance on-board data processing and telecommunications with the host ESPA spacecraft. High efficiency solar panels, energy storage systems, deployables, autonomous rendezvous, positioning, and docking, and advances in attitude control mechanical systems that do not rely upon moving parts (i.e. elimination of reaction wheels assemblies).



5.4 Concurrent Engineering: ExCSITE In Detail

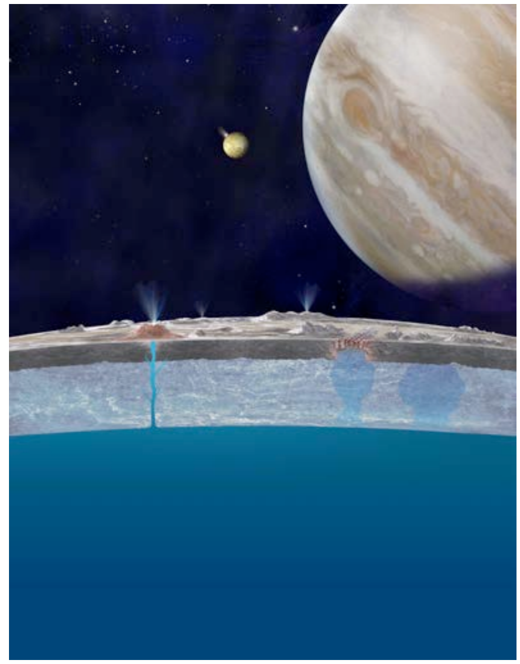
The ExCSITE mission concept, Explorer CubeSat for Student Involvement in Travels to Europa, was introduced by Castillo-Rogez et al. (2013) and further developed as part of this study. Surviving the radiation environment, both in transit and in operational proximity within the Jovian system, is paramount. Nevertheless, this mission concept also involves multiple CubeSats that act as fly-by imagers, impactors, and sub-surface geophysical explorers where a series of new technologies ranging across autonomous systems, radiation and impact shielding, multi-spacecraft telecom, in-situ sampling



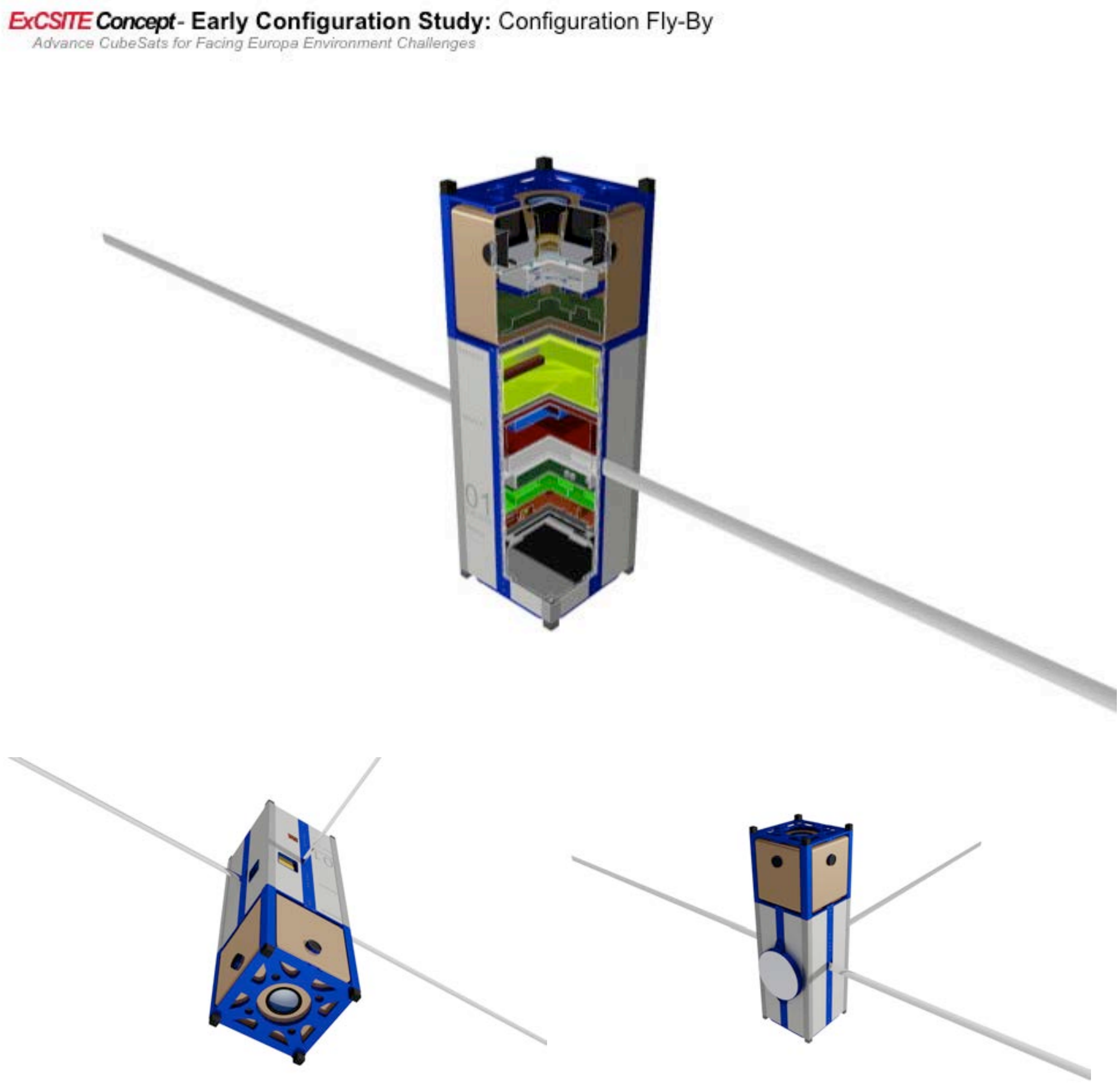
and exploration, and planetary protection (to name a few) would all be needed to achieve the mission concept objectives.

The basic structure of the impactor CubeSat is shown above, but note that all of the CubeSats for this concept would have a plug-and-play design utilizing the same radiation hardened spacecraft bus. For the impactor, the blue tip is fabricated using metallic glass (a highly impact resistant material) along with graphene for the main exterior structure to support the upper stage. The remaining structure is 3D printed aluminum that would be designed to withstand, or absorb, impact loads to guarantee the preservation of the instrumentation integrity. The upper section is the warm chamber that would house instruments including high speed and resolution cameras, spectrometers, and other observational systems. For the impact scenario this section would be pre-heated where internal high performance battery systems could be applied to support a melt-down processes (to within a few centimeters) for in-situ sub-surface exploration.

Since this mission concept calls for an impactor planetary protection requirements will need to be satisfied. DHMR, Dry Heat Microbial Reduction, is the technique most often used to "bake out" traditional spacecraft, but methods that would be more amenable to sensitive components and to smaller systems could be applied such as aseptic assembly. In this way, exposure levels can be targeted on a component-wise basis based on exposure requirements to the planetary surface and the system could be assembled and packaged in a "clean" fashion that would be essential for future integration with CubeSat deployer systems that must also meet such stringent requirements.



This concept also has fly-by spacecraft that would produce high-resolution near-surface imagery as well as spectroscopy from dust ejecta produced by another (potentially "dumb" in this case) impactor spacecraft. Although effort would be placed into dispenser trajectory analysis from the host spacecraft these CubeSats would require an autonomous system to plan and execute proximity operations post-deployment to ensure the best possible targets and imaging capabilities would be met. Furthermore they must be in constant communication with the host spacecraft during this process to ensure all data is successfully transmitted before termination of their role in the experiment. Finally, advances in power system technology will be needed as solar cells would be ineffective at that distance from the Sun and battery technology capabilities would be limited. Advancing the development of compact radioisotope thermoelectric generator technology would enable this concept as well as all beyond LEO SmallSat systems that are based on CubeSat and NanoSat form factors.



References

Castillo-Rogez, J. C., Klesh, A. T., Kahn, P., Staehle, R., Nesnas, I. A. D., Pavone, M. (2013) Next generation SmallSat – Dare to explore where no craft has gone before, presented at the 10th Low Cost Planetary Mission Workshop, Pasadena, June 2013.

5.5 Disruptive Trajectory and Mission Design Technology

One of the issues with SmallSat missions is the fact that although the cost of the spacecraft hardware may be greatly reduced, the amount of work required to design and navigate the mission may not always be reducible to the same extent. In fact, in some cases, the trajectory design, attitude control, and navigation may require more analysis than for conventional missions due to the configuration of small spacecraft system design such as propulsion, maneuverability, etc.…

A fact that is not always appreciated is that trajectories are not absolute objects, but are relative in nature. This means that depending on the situation, how one describes a trajectory can be drastically different. For a particular mission, due to factors like the geometry, spacecraft design (propulsion, attitude control, communications, solar panels, science requirements, etc.), and dynamics of the physical forces involved, special coordinates and coordinate frames may be needed. For example, in the Three Body Problem, we find it advantageous to use Cartesian coordinates in a rotating frame because this greatly simplifies the mathematics and geometry. Orbital elements in this situation do not work well, if at all, since they are adapted to the Two Body Problem. This relativity of the representation of trajectories means that as spacecraft technologies change and science requirements become more demanding, the trajectories also need to adapt to these changes and advances which require research and development. Trajectory design is a technology that requires continual R&D as does any other technology required for space missions. In fact, it is perhaps one of the most cost effective and enabling of space technologies. A good orbit can literally get you there cheaper and faster, wherever “there” might be in space, thus pursuing new approaches supports advancing small spacecraft mission concepts.

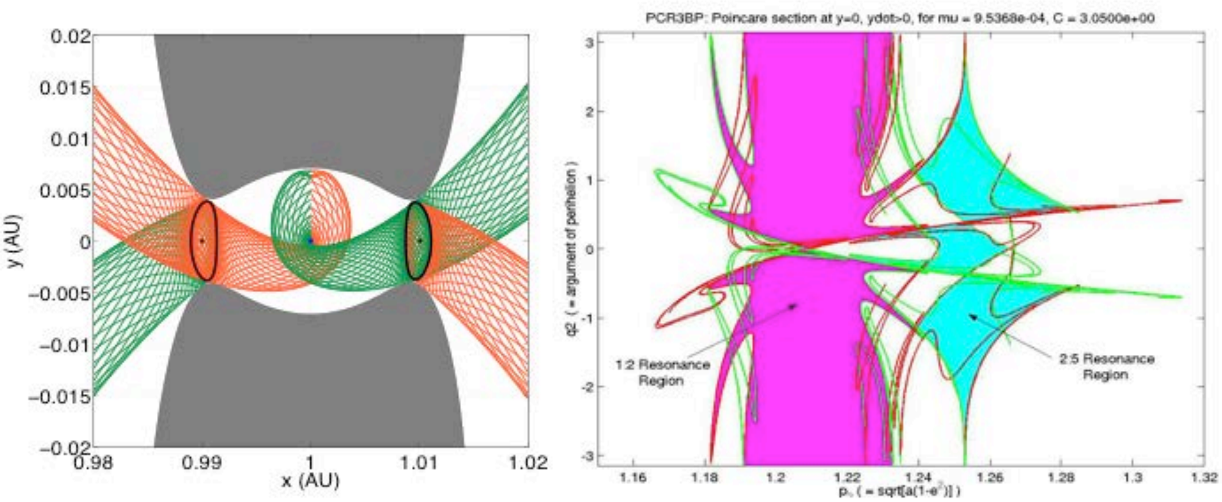
What is it about small satellites that require new trajectory technologies? Actually, the issue is not due entirely to small satellites; it is in fact a broader issue with the increasing use of continuous low thrust engines and nonlinear trajectories for space missions. These two technologies push the envelope of our current mission design capabilities. This affects not only the exotic missions that NASA is planning, but also missions around the Earth for the US military and commercial aerospace communities. In 2012, the National Research Council (NRC 2012a) issued a report recommending the US Air Force develop a new astrodynamics standard in order to address the difficult problems of Space Situational Awareness and Space Debris, because the old orbital mechanics is no longer adequate for solving these hard problems. One of the technologies the NRC recommended is Dynamical Systems Theory that was created by Poincaré precisely to address highly nonlinear problems such as our orbital issues. Furthermore, the NRC 2012b also recommended technology development for trajectory design for small bodies, however expanding this action to address the overall broader nonlinear astrodynamics standards would be highly desired. Indeed, addressing the complex orbital dynamics involving 3, 4, and N-Bodies, not just the 2-Body Problem, would be ideal.

The combined message of the two reports clearly signals that new orbital technologies are needed to support the new classes of missions that have emerged in the 21st century. The class of SmallSat missions is clearly one of these driving the need for new orbital trajectory technologies.

Nonlinear orbital mechanics is a huge discipline since all non-Keplerian orbits are nonlinear. Even Keplerian orbits can become highly nonlinear under continuous thrust or solar radiation pressure. In fact, continuous thrust changes the trajectory problem from the finite dimensional domain to the infinite dimensional domain. This combination of nonlinear problems in infinite dimensions is what makes modern trajectory design and optimization such a difficult problem. The nonlinearities are created by the continuous thrust, the dynamics of the Three (or more) Body Problem (e.g. low energy orbits), and the irregular shapes of small bodies or space debris. For large spacecraft, some of the nonlinearities may be overcome through sheer force. For example, the Lunar Flashlight CubeSat mission concept, under investigation via NASA's Advanced Exploration Systems Program, seeks to map the lunar polar regions for ice in a 20 km circular orbit. A conventional spacecraft can use a Hohman transfer to capture into a 20 km circular orbit around the Moon without much trouble. But, for a CubeSat using a small solar sail, this requires a nearly year-long spiral trajectory which must go through multiple regions of overlapping resonances that create tremendous instability which can easily lead to a loss of mission. This example shows that with SmallSats, we can no longer ignore the chaotic regions of phase space. We need to understand the dynamics of these chaotic regions in order to avoid them where possible, and finesse them through nonlinear control when necessary. The mapping of these chaotic zones and the development of new orbital techniques to sail through them are two key research problems that need to be addressed.

But these chaotic zones are also a blessing because they are what make up the "Interplanetary Superhighway". It is the chaos which provides the low energy orbits used by missions like Genesis, MAP, ARTEMIS, GRAIL, and even Galileo and Cassini. But the chaos is a two edged sword. In some instances they help us tremendously, while in others they can easily crash our spacecraft. The problem is that each chaotic regime behaves differently and must be analyzed and mapped out individually. Where there are arching theoretical understandings of these regimes, to actually use and exploit them still requires analysis and development. For example, in the 1960s we first began to understand how resonant planetary flybys can provide an extra kick to the spacecraft. This led to the development of tour designs for Voyager, Galileo, and Cassini. It is not well known that the dynamics behind the flyby is provided by nonlinear effects of the Three Body Problem. In the 1990s, we began to understand the role of chaos in libration missions that led to the design of missions like Genesis, ARTEMIS, and GRAIL. SmallSat mission to regimes like the moon and small bodies present yet another extremely challenging regime discussed next.

The shape of bodies can greatly affect the orbits. Even with the shape of the Earth, we know the orbit plane will precess in several ways, which must be taken into account in any Earth mission. But, with small bodies, their shapes can be drastically distorted compared to the Earth. Even with an elongated ellipsoid, this creates very complex orbital dynamics around the small body. For example, low energy orbits develop which generate tubes that can land on the small body or launch from the small body. This is great for a landing mission, but creates instability for an orbiting mission that can lead to a crash. In particular, with small bodies, the mass and shape of the spacecraft can no longer be ignored and must be integrated into the mission design. Thus, the trajectory design, the attitude control algorithm, and the navigation of the spacecraft can no longer be separately designed and implemented. Instead, they must be



(Left) This shows the tubes of trajectories that connect a halo orbit at L1 (black orbit, left) with a halo orbit at L2 (black orbit, right). The Moon is at the center of the page. The Earth is to the left of the figure, way beyond and not shown. The green trajectories approach the halo orbits, the red trajectories move away from the halo orbit. When the tubes intersect, they provide transfer from one tube to the other. This is what creates the low energy transport system called the Interplanetary Superhighway.

(Right) This diagram is a cross section of the tubes in Delaunay variables. The magenta region is one resonance; the cyan region is another resonance. The red and green curves are the cross section of the tubes like those in Fig. 1a in these transformed coordinates. The intersection of the red and green curves create the chaotic transport. And the resonances are in overlap that creates additional chaos in the system.

integrated from the start. These same issues, perhaps not as prominently displayed, are also inherent in the use of the solar sails within a highly nonlinear environment.

The R&D of these research topics has far reaching consequences beyond SmallSats. Ultimately, by creating these new mission capabilities for the current generation of small satellites, we also lay the foundation for an integrated system for mission design, attitude control, and navigation. This foundation is needed for future spacecraft that may be completely autonomous. In a real sense, SmallSats are stepping stones and testbeds for the integration process of these different disciplines needed for on-board autonomy and complex trajectory design for the class of concepts described here.

References:

National Research Council, “Continuing Kepler’s Quest: Assessing Air Force Space Command’s Astrodynamics Standards”, 2012, National Academies Press, Washington, D.C.

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6 Findings, Recommendations, and Closing Thoughts

In the time period since these workshops have concluded the interest in the role small satellites can play in advancing space science has grown tremendously. Scientists are asking new questions, as the technical capabilities of these systems become better understood and increasingly appealing. New lines of investigation are being formulated and the community is invigorated with the potential that exists to complement and expand the role of traditional missions while opening new thrusts in astrophysics, heliophysics, and planetary science.

It was an ambitious undertaking to explore three major scientific disciplines within the context of new investigations that may be performed given new platforms such as small satellites. While the teams have pursued new exploration concepts, one of the near-term tangible outcomes of this exercise was to identify recommendations that would enable such missions in the future.

Recommendations	Impacts
Beyond LEO SmallSat Science Exploration Program	A means to establish a roadmap and set of scientific objectives tailored specifically to unique small satellite observations in astrophysics, heliophysics, and planetary science. This would include an expansion of the SMEX and mission of opportunity programs to include development of a robust set of small satellite constellation survey missions.
Beyond LEO SmallSat Technology Maturation Program	The means to advance hardware and software technologies, including instruments, to enable long duration and resilient small spacecraft systems compatible with deep space scientific exploration.
Small Spacecraft as Secondaries on All Beyond LEO Missions	Establishing this capability adds value to flagship mission science observation, specifically where measurements are desired in extreme environments or high risk circumstances to the primary, with manageable risk at low cost.
Dedicated SmallSat Launch and Operations Program	A program targeted to this recommendation for beyond LEO small spacecraft systems. This includes investments in ground station capabilities and associated infrastructure to support beyond LEO deployment, telecom, and tracking.
Targeted "Class D" Proposal Opportunities for Beyond LEO SmallSat Missions	The current peer-review process can impede the ability to propose single small satellite missions, as they must compete against higher-class instruments and spacecraft within the same scientific guidelines. This recommendation would support a means to assess how innovative approaches could target specific scientific advances using new platforms.

These are recommendations and outcomes for the scientific and engineering community at large; not for any specific agency although there are national and international government and industry organizations that could act upon them.

Nevertheless, even within the context of these recommendations progress on beyond LEO CubeSat technical development is underway. Robert Staehle of JPL had considered the potential of CubeSats for interplanetary exploration via a NASA Innovative Advanced Concepts (NIAC) investigation he led in 2011 called "Interplanetary CubeSats: Opening the Solar System to a Broad Community at Lower Cost". This work was among the first formal efforts to outline many of the key considerations, including taxonomy, of technologies that could be applied to the development of CubeSats for beyond LEO exploration. Furthermore, the INSPIRE mission, led by Andy Klesh of JPL, will be the first pair of CubeSats deployed on an Earth escape trajectory to test various technologies that may be needed for beyond LEO CubeSat exploration. INSPIRE delivered flight hardware in June of 2014 for a near-term launch opportunity. Also, NASA's Advanced Exploration Systems program selected three 6U CubeSat mission concepts in August 2013 for further development that would address key strategic knowledge gaps for the Human exploration of the Moon and Near Earth Asteroids. These missions are Lunar Flashlight (JPL/MSFC), NEAScout (MSFC/JPL/LaRC/JSC/GSFC), and BioSentinel (ARC).

Some of the concepts from this report have been refined even further by study team members through advanced concept studies since the workshops concluded and great progress has been made in overcoming technical hurdles to bring these ideas to fruition. These kinds of actions will represent the legacy of the study group; that is to form a community, rethink approaches to space science observation, and to bring forward innovative methods to establish new capabilities for exploration of the universe beyond low Earth orbit.

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7 Summary of Workshop Presentations

Presentations from the workshop study sessions, as well as the plenary public lecture series, can be found from the study program web page:

http://www.kiss.caltech.edu/study/smallsat/

Selected papers and other media are available from the study website as well.

8 Acknowledgements

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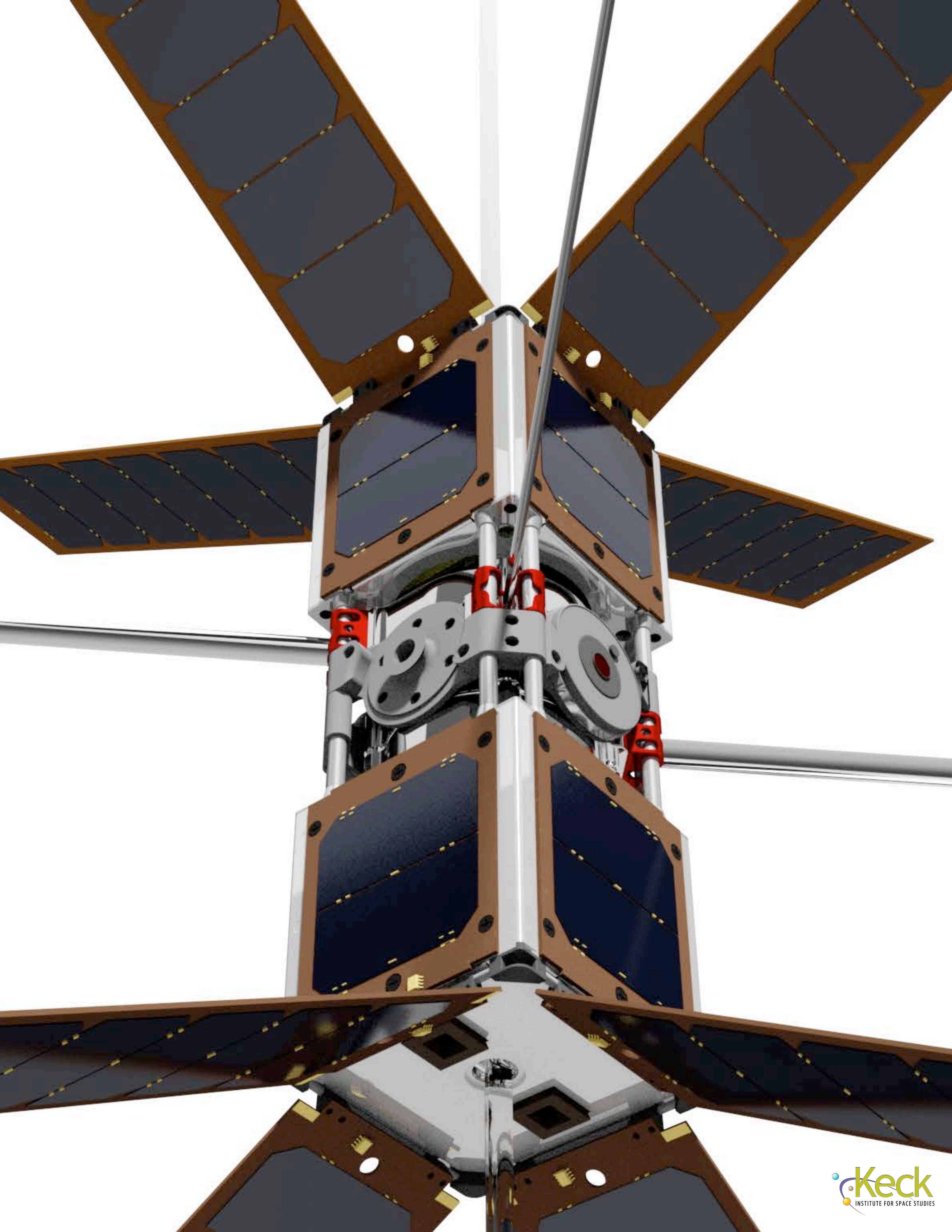

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